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Life Cycle Inventories of Bioenergy

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TP1: Life Cycle Inventories of Bioenergy

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TP1.c: LCI of modern biogas plants and organic rape seed

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A further co financing from alcosuisse, Erdöl-Vereinigung, and Entsorgung und Recycling Zürich made it possible to investigate a number of further datasets. Furthermore the collaboration with industrial partners, non governmental organisations and public authorities in the review group helped to improve the quality of the investigated datasets. We thank all people involved in the review work.

The data have first been used and evaluated by the EMPA St. Gallen for their LCA study of different biofuel production chains (Dinkel 2007; Kägi et al. 2007; Zah et al. 2007). We thank the authors of these reports for further comments and hints on possible errors.

Summary

Today, transportation relies almost entirely on oil-based fuels and is responsible for about 30% of the world's fossil fuel consumption. According to the principles of sustainability, a modern society should preserve non-renewable energy sources and replace them with renewable energy. The depletion of fossil energy reserves and the associated environmental impacts are the two main reasons that lead to consider the use of alternative fuels in the sector of transportation.

Fuels derived from biomass, also referred to as biofuels, are not only potentially renewable, but are also sufficiently similar to fossil fuels (which also have their origin in biomass) to provide direct substitution. It seems also to be a promising alternative to fossil fuels in the short term.

The goal of this project, which has been initiated by the Swiss Federal authorities BFE, BLW and BAFU, is to investigate life cycle inventory data of several energy products from biomass. These data shall complement existing datasets in the ecoinvent database and should become available in a future version of this database. Therefore the same methodology is used as in the ecoinvent project (Frischknecht et al. 2007a).

Some types of biomass and their energy products have already been investigated for the ecoinvent database, e.g. agricultural products (Nemecek et al. 2007), renewable materials (Althaus et al. 2007b) or wood products (Werner et al. 2007) as well as their use in combustion processes (Bauer 2007). Nevertheless many possible uses of biomass for energy purposes were so far not covered by the database.

Fig. 1.1 provides a systematic overview for the different types of bioenergy that are of interest. In general, four stages of production can be distinguished (provision of the biomass, conversion to a fuel, distribution and use).

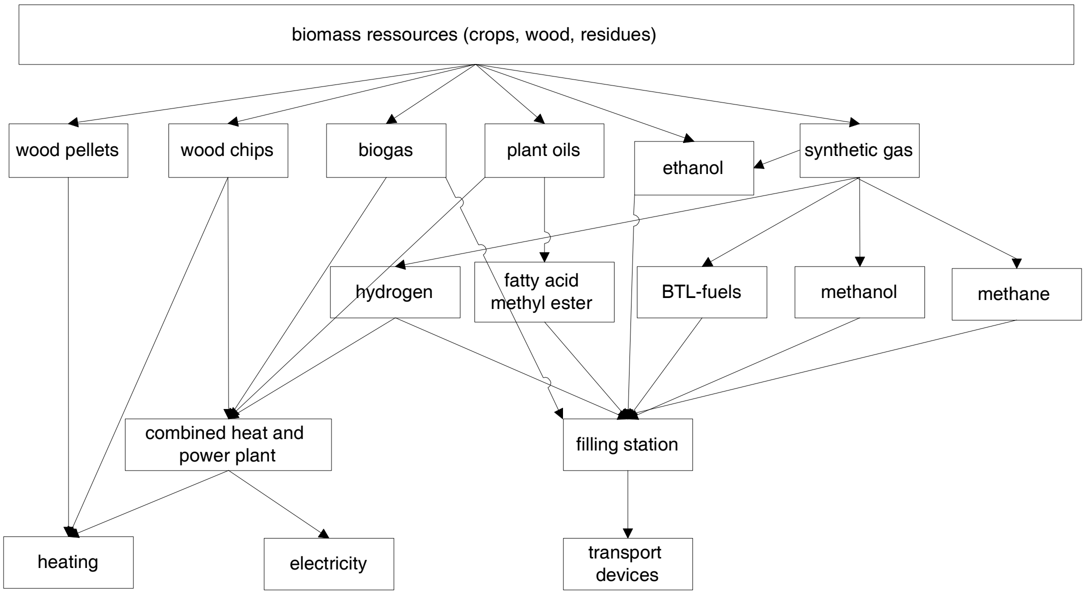

Fig. 1.1 Overview for the most important bioenergy products and their possible uses

In a pre-study the existing datasets of the ecoinvent database have been systematically organized (Jungbluth & Frischknecht 2004). The study helped to identify all missing process chains and unit processes in order to be able to define the bioenergy products of interest for the situation in Switzerland.

The following products are already covered with the ecoinvent data v1.2:

- Forestry
- Agricultural products from Switzerland

- Wood fuels
- Use of wood for heating and CHP

Within the first part of this project, the production and use of ethanol, biogas, BTL-fuels (biomass to liquid i.e. methanol) and plant oils have been investigated. Therefore agricultural products that are needed for these fuels (grass, straw, rape seeds) are included in the analysis. The use of biofuels in different means of transportation is investigated as well.

In the second part of the project a specific focus has been laid on biofuels imported to Switzerland. Therefore basic LCI data have been collected for biomass production and biofuel conversion in different countries. In this part of the project also to day and future conventional transport means have been included in the analysis.

In a third part of the project an inventory has been investigated for modern biogas plant with a cover on the storage which minimizes the methane emission. Also preliminary data for organic rape seed have been revised.

The calculation of cumulative results is based on ecoinvent data v1.2 (or partly ecoinvent data v1.3). It has been executed by the ecoinvent Manager with a copied version of the original database and with the same calculation routines.

It was not possible to cover all possible uses of bioenergy within this project due to financial limitations. The most important gaps that remain are the following:

- Full investigation of all possible production routes. Only the most important routes have been investigated.
- Use of some bioenergy carriers, e.g. plant oil, in heating and combined heat- and power plants.

In the impact assessment part of the project different options for the use of bioenergy are compared and analysed in a full life cycle assessment (Dinkel 2007; Kägi et al. 2007; Zah et al. 2007).

Zusammenfassung

Im Rahmen von verschiedenen Studien wurden bis heute Energieprodukte hinsichtlich ihrer Umweltauswirkungen untersucht. Dabei wurden nicht erneuerbare (fossile) Energieträger untereinander, aber auch mit erneuerbaren verglichen. Die Untersuchungen aus der Schweiz beschränken sich jedoch meist auf einzelne Umweltbereiche oder beleuchten nur einzelne Aspekte der Umweltauswirkungen. Zudem sind bei biogenen Energieträgern die Anbaumethoden und -varianten nicht systematisch untersucht worden.

Um einerseits im Forschungsprogramm Biomasse die richtigen Schwerpunkte setzen zu können und andererseits in der politischen Diskussion im Bereich Energie-, Umwelt- und Klimapolitik über die entsprechenden Entscheidungsgrundlagen zu verfügen, werden umfassende Ökoinventare von (Bio-)Energieprodukten erarbeitet, die alle relevanten Umweltbereiche gleichermassen berücksichtigen und sowohl biogene als auch fossile Energieträger umfassen.

In der Datenbank ecoinvent gibt es bereits zahlreiche Datensätze zu diesem Thema, z.B. zu

- Holzprodukten und Holzbrennstoffen
- Landwirtschaftsprodukten aus der Schweiz
- Holzheizungen und Kraftwerke

Die Ökoinventare sind modular (Prozesse bzw. Prozessketten) aufgebaut, sodass eine Erweiterung und eine Bilanzierung von weiteren Anwendungsfällen einfach möglich ist. Folgende Wertschöpfungsebenen werden dabei unterschieden:

- Landwirtschaftliche und forstwirtschaftliche Produktion (bzw. Bereitstellung von Reststoffen und Nebenprodukten)
- Verarbeitung, Herstellung der Brenn- und Treibstoffe
- Evtl. Bestimmung eines Produktionsmixes
- Distribution bis zum Endverbraucher
- Verwendung der Energieträger für Fahrzeuge, Heizungen, etc.

Im ersten Teilprojekt (TP1, „LCI bioenergy“) wurden fehlende Sachbilanzdaten für alle wichtigen Produktionsstufen und Verfahren erhoben soweit sie nicht schon bisher Bestandteil der ecoinvent Daten v1.2 waren. Dabei wurden die Themen „**Biogas**“, „**Ethanol**“, „**BTL/synthetische Treibstoffe**“, „**Öl**“, „**Transport**„ und „**Sonstige**“ bearbeitet.

Im zweiten Teilprojekt (TP1.b, „LCI of imported fuels“) lag der Schwerpunkt dann auf der Bilanzierung von Treibstoffen, die u.U. in die Schweiz importiert werden können. Ausserdem wurden noch fehlende Inventare für die Schweiz nacherhoben und aktuelle Transportprozesse untersucht.

Im dritten Teilproject (TP1.c Biogas) wurde ein neuer Datensatz für moderne landwirtschaftliche Biogasanlagen mit Abdeckung der Nachgärung bilanziert. Diese minimiert die Methanemissionen. Ausserdem wurde der Datensatz für biologisch angebauten Raps mit neuen Daten überarbeitet.

Die Erhebung erfolgt entsprechend der Qualitätsrichtlinien für das ecoinvent Projekt (Frischknecht et al. 2007a).

Erhoben werden nur die notwendigen Grundlagendaten der wichtigsten Prozessschritte für die Bereitstellung von Biomasse-Energieträgern. Es werden jedoch nicht alle Varianten gerechnet (z.B. Lkw mit Ethanol aus Mais (Bio/IP) und Lkw mit Ethanol aus Weizen Bio/IP) sondern jeweils nur Durchschnittsbetrachtungen auf der Nachfolgeebene durchgeführt (z.B. nur Lkw betrieben mit Ethanol-Produktionsmix).

Im zweiten Teil des Gesamtprojektes werden die erhobenen Daten in einer Gesamtökobilanz bewertet und verschiedene Treibstoffe und Herstellungswege miteinander verglichen (Kägi et al. 2007; Zah et al. 2007).

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Part I

I. Methodological Remarks

Author: Niels Jungbluth, Mireille Faist Emmenegger, ESU-services Ltd.

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1 Introduction

1.1 Goal of the project

Today, transportation relies almost entirely on oil-based fuels and is responsible for about 30% of the world's fossil fuel consumption. According to the principles of sustainability, a modern society should preserve non-renewable energy sources and replace them with renewable energy. The depletion of fossil energy reserves and the associated environmental impacts are the two main reasons that lead to consider the use of alternative fuels in the sector of transportation.

Fuels derived from biomass, also referred to as biofuels, are not only potentially renewable, but are also sufficiently similar to fossil fuels (which also have their origin in biomass) to provide direct substitution. It seems also to be a promising alternative to fossil fuels in the short term.

The goal of this project, which has been initiated by the Swiss Federal authorities BFE, BLW and BAFU, is to investigate life cycle inventory data of several energy products from biomass. These data shall complement existing datasets in the ecoinvent database and should become available in a future version of this database. Therefore the same methodology is used as in the ecoinvent project (Frischknecht et al. 2007a).

Some types of biomass and their energy products have already been investigated for the ecoinvent database, e.g. agricultural products (Nemecek et al. 2007), renewable materials (Althaus et al. 2007b) or wood products (Werner et al. 2007) as well as their use in combustion processes (Bauer 2007). Nevertheless many possible uses of biomass for energy purposes were so far not covered by the database.

Fig. 1.1 provides a systematic overview for the different types of bioenergy that are of interest. In general, four stages of production can be distinguished (provision of the biomass, conversion to a fuel, distribution and use).

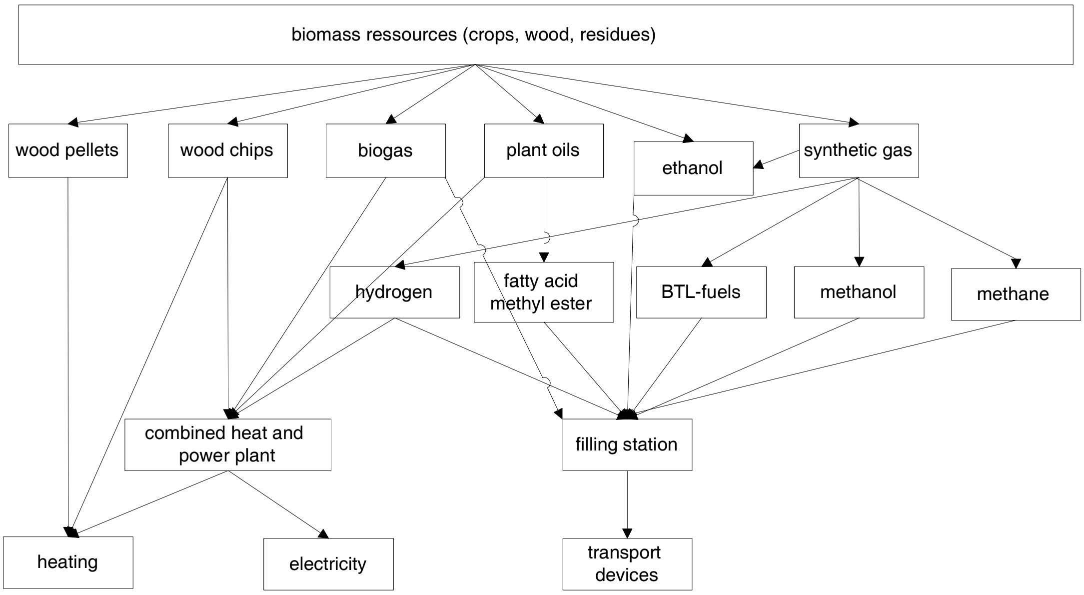

Fig. 1.1 Overview for the most important bioenergy products and their possible uses

In a pre-study the existing datasets of the ecoinvent database have been systematically organized (Jungbluth & Frischknecht 2004). The study helped to identify all missing process chains and unit processes in order to be able to define the bioenergy products of interest for the situation in Switzerland.

The following products are already covered with the ecoinvent data v1.2:

- Forestry
- Agricultural products
- Wood fuels
- Use of wood for heating and CHP

Within the first part of this project, the production and use of ethanol, biogas, BTL-fuels (biomass to liquid i.e. methanol) and plant oils have been investigated. Therefore agricultural products that are needed for these fuels (grass, straw, rape seeds) are included in the analysis. The use of biofuels in different means of transportation is investigated as well.

In the second part of the project a specific focus has been laid on biofuels imported to Switzerland. Therefore basic LCI data have been collected for biomass production and biofuel conversion in different countries.

The calculation of cumulative results is based on ecoinvent data v1.2. It has been executed by the ecoinvent Manager with a copied version of the original database and with the same calculation routines.

It was not possible to cover all possible uses of bioenergy within this project due to financial limitations. The most important gaps that remain are the following:

- Full investigation of all possible production routes. Only the most important routes have been investigated.
- Use of some bioenergy carriers, e.g. plant oil, in heating and combined heat- and power plants.

In a second part of the project different options for the use of bioenergy are compared and analysed in a full life cycle assessment (Dinkel 2007; Kägi et al. 2007; Zah et al. 2007).

1.2 Natural conditions for biomass production in Switzerland

Switzerland has an area of 41'285 km^2. Jura, Lowlands and the Alps are the three geographical main regions. Switzerland has a very high population density: on average, about 183 people live on 1 km2. The difference between the regions are however high: in the Alps, which have a great share of the country’s surface, lives only about 10% of the population.[1]

The alpine arch has a length of 800 km and a broadness of ca. 200 km as well as an average altitude of 2500 m over sea and acts as a climate barrier. Climate in the Swiss Alpine region is divided in the North and the South region. In the Northern part of the Alps maritime climate is dominating. The Southern part of the Alps is dominated by Mediterranean climate, which mean milder winters. Some valleys are protected against Northern and Southern precipitation activities. Consequence is a dry climate: typical for this kind of climate are Unterwallis and Engadin valleys.[2]

The following table gives some key figures of the climate in Switzerland in 2003.

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[1] http://www.swissworld.org/ger/swissworld.html?siteSect=201&sid=4147667&cKey=1061372946000&rubricId=10010

[2] source: Meteoschweiz, www.meteoschweiz.ch

Tab. 1.1 Key figures of the climate in Switzerland (average 1961-1990).

	altitude	Sunshine duration	Precipitation quantity	Temperature of air (year average)
	m. o. s.	h	mm	°C
Basel	316	1599	778	9.6
Bern	565	1638	1028	8.2
Chur	555	1702	814	8.7
Davos	1590	1680	1082	2.8
Genève	420	1694	970	9.8
Locarno Monti	366	2155	1668	11.5
Lugano	273	2026	1545	11.6
Luzern	456	1322	1171	8.8
Neuchâtel	485	1549	932	9.3
Sion	482	1990	598	9.2
St Gallen	779	1390	1248	7.4
Zürich	556	1482	1086	8.5

source: http://www.meteoschweiz.ch/de/Daten/Messwerte/IndexMesswerte.shtml, downloaded 3.10.2005

The length of growing period is 115-180 days in the Subalpine zone (1700-2400 m.o.s.) and 180-245 days in the mountainous zone (1000-1700 m.o.s.). Typical soils in the Alps are silica rocks with little humus.

1.3 Reserves and resources for bioenergy in Switzerland

Switzerland has mostly small sized farms with an average of 16.2 ha (19.9 ha when considering only full-time farmers). The intensity of production is therefore relatively low. Due to climatic differences between Lowlands and Alps and between South and North, the agriculture is regionally specialised. In the Alps there is mostly animal production as well as forestry.

Agriculture in the Alps is strongly dependent from subsidies. Subsidies are however linked to ecological requirements. Agriculture in the Lowlands is e.g. following the principles of integrated production (IP) as a consequence of the policy on subsidies. About 10% (102'000 ha in 2002 from the total of 1.07 Mio ha) is organic agriculture (mainly grasslands).[3] Important amounts of agricultural products, e.g. fodder and food are imported to Switzerland. Cheese is an important exported product.

Agriculture in Switzerland employs about 200'000 persons.[4] Hersener and Meier (1999) assume that fallow land will grow to 6’000 ha in 2010. This increase takes place at the expense of meadows.

Due to the nature of its mountainous landscape, Switzerland is a country of large forested lands. Forest residues are the primary biomass resource in Alpine countries. Wood industry by-products are widely used for energy production in the wood processing industry, district heating and for pellets production. Wood industry by-products potentials for transportation fuels are limited. No straw surplus for energy uses exists due to the fact that all straw is used for agricultural purposes.

In the most actual study for Switzerland (BFE/EWG 2004) the authors use several definitions of potential:

- Supply potential (Angebotspotential): generic term for theoretical biomass potential and realisable resp. ecological potential biomass potential for energy use.

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[3] http://www.biodiversitymonitoring.ch/pdfs/M5_Datensatz_V2.pdf, 3.5.05

[4] http://www.bauernverband.ch/de/markt_preise_statistik/betrieb/se_2003_0112.pdf, figure for 2003, 3.5.05

- Theoretical (biomass) potential: grown biomass on arable land and material from secondary production thereby incurred in national economy.
- Ecological net production potential: biomass that can be produced on a sustainable and efficient (positive energy balance) way in the agriculture and forestry.
- Potential of disposal with energy recovery: share of industrial and urban biomass residues and waste that can be used for production of energy.

1.3.1 Energy crops

Several energy crops can possibly grow in Switzerland. Hersener and Meier (1999) calculate with following yields for energy crops:

Rapeseed	3 t DM/ha
Miscanthus	18 t DM/ha
Hemp	12 t DM/ha
Kenaf	3 t DM/ha
Buffer area	3 t DM/ha

According to (BFE/EWG 2004), the share of energy crops is expected to increase to 5% of the open agricultural crop land, which corresponds to 20’000 ha until 2025, with a yield of about 10 t DM/ha. From 2025 to 2040 the authors evaluate the increase to be 10% of the open agricultural crop land, which corresponds to 45’000 ha. This increase occurs at the expense of intensively farmed crops like turnips, cereals, maize and intensive meadows.

1.3.2 Meadows

This category includes fallow land, extensive farmed meadows and permanent meadows (which have the biggest share of this category). Alpine meadows' potential is considered in the category "a) forest", as the increase in forest area occurs at the expense of alpine meadows. The yield of meadows for energy use is estimated by the authors of (BFE/EWG 2004) at 1% of yearly total yield until 2025. Optimistic scenarios evaluate the potential to be 3%.

1.3.3 Agriculture residues

Arable land in Switzerland covers 26% of agricultural land. Cereals are not dominant.

Tab. 1.2 Cereal production in Switzerland (Hersener & Meier 1999)

Arable land	Cereal area	Cereals share in arable land	Cereals yields 1998-2002
1000ha	1000ha	%	t/ha
413	136.1	30	6.1

The following agricultural products and residues for energy use are taken into consideration in Switzerland[5]:

- Rape seed oil, miscanthus, hemp, grass, hedges

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[5] Personal communication, Hersener J.-L., Wiesendangen, Email 3.6.2004.

- Products from landscape care (areas of nature protection, residues of mowing of reeds etc.),
- Straw and other harvest residues.

Actually about 3,700 t DM (dry matter) of agricultural products (0.1 PJ) and 7,800 t DM (0.1 PJ) agricultural residues are used for energy production in Switzerland. This corresponds to 0.2 PJ primary energy. Hersener evaluate that the total potential of agricultural products is up to 305'000 t DM (4.6 PJ), of products of landscape care to 25'000 t DM (0.4 PJ) and agricultural residues to 38'000 t DM (0.6 PJ). This would raise available primary energy to 5.6 PJ. The ecological potential of agricultural products and residues in the future is estimated at 5.6 PJ (Hersener & Meier 1999).

Straw is used in Switzerland for litter and must even be imported (Hersener & Meier 1999). There is no straw surplus in Switzerland. Straw in dung from litter can be used as energy, however only in power plants bigger than at least 500 kWth. Due to the structure of agriculture and restricted possible sites, the share of straw, which can be used as energy in dung, must be estimated to be only 1% (Hersener & Meier 1999).

1.3.4 Forestry

Actually, about 10% of the Swiss forests are used for energy production. The total energy in biomass products of forests, orchards and vineyards was 17.7 PJ in 1998. The forest has two kinds of potentials: an increase in the harvest use and an increase in the harvest itself. From the first one ($1.8*10^6$ m^3 harvested wood that actually stay in the forest) the potential is evaluated to be about $1.2*10^6$ m^3 (2/3 of this quantity), which corresponds to about 9 PJ/a. For the second potential the authors calculate with the $4.2*10^6$ m^3 of forest increment that are at present not harvested. From these also 2/3 are evaluated to be possible to harvest, which represent 21.7 PJ/a. Production of bark in the year 1999 was at the level of 0.7 Mm^3 (4.83 PJ) and utilization for energy at 0.4 Mm^3. Thus surplus of bark that could be used equals 0.3 Mm^3 (2.07 PJ) (Hersener & Meier 1999).

For woody crops and hedges the potential is evaluated to be $0.35*10^6$ m^3, which corresponds to 2.8 PJ/a.

With an increase in the degree of utilization of forest area, groves, orchards and vineyards, the potential of biomass in the future would be 44 PJ, thereof the biggest share would be from forest areas (BfS/BUWAL 2003).

1.3.5 Wood industry by-products

The recycling rate of paper and waste wood as well as utilization grade is already high, so that there is only little potential of increase for this category. Some studies estimate that waste wood and waste from the paper/cardboard industry used for energy production amounted to 21 PJ in 2001. The possible increase in the degree of utilization of these residues is estimated as low, as recovery grade and utilization grade are already quite high (Hersener & Meier 1999). Therefore the calculated ecological potential for 2040 is 24.2 PJ, only 3.4 PJ more than in 2001.

According to national studies (BfS/BUWAL 2003) wood industry by-products production amounts to about 0.8 Mm^3. These are already fully used.

1.3.6 Whey

About 1.5 mio. m^3 of whey are produced in Switzerland per year (Binggeli & Guggisberg 2004; Scheurer & Baier 2001). Actually about 90% of waste of the food industry goes to the animal husbandry and is used as fodder (Scheurer & Baier 2001). Alternative use for whey is the production of biogas or bioethanol. According to (BFE/EWG 2004), the actual use of food industry waste for energy production is about 3% (of all waste). They expect this share to stay quite constant and grow only to 5%. The same study cites other (more optimistic) sources which expect the share of food industry waste for energy production to grow to 20%.

1.3.7 Development perspectives

The position paper of the Swiss Agency for Environment, Forests and Landscape (SAEFL) on the energetic use of energy crops shows that the intensive production is not favoured any more. The energetic use of energy crops from extensively farmed areas like meadows, ecological buffer area, set-aside land etc. is however welcomed (Binggeli & Guggisberg 2003).

In the context of a common project of the Swiss Federal Office for Energy with the Swiss Agency for Environment, Forests and Landscape, the most important process chains of the production of energy out of biomass have been studied and compared. The experiences with pilot and demonstration plants show that the general framework is of great importance for the development of the energetic use of biomass. The following points are discussed to promote and increase the use of biomass for energy production:

- Electricity redelivery tariff, tax on CO_2, promoting programs
- Exemption of tax for biofuels
- General promoting of biofuels and their sources

1.3.8 Economical feasibility

BFE/EWG (2004) studied the costs of the production of bioethanol on the basis of ligno-cellulose biomass in Switzerland. Borregard Schweiz AG is the biggest producer of ethanol in Switzerland with a yearly production of 11 million litres ethanol. It plans a new plant that will produce bioethanol out of ligno-cellulose by 2010. The costs of the production of bioethanol is divided in feedstock transport costs (14%), feedstock non-transport costs (30%), investment costs (43%), fixed operating costs (9%), variable operating costs (4%). The total price in 2010 is estimated to be 1.46 CHF/l (comparison: conventional gasoline would be 1.37 CHF/l), in 2025 1.15 CHF/l (conventional gasoline 1.87 CHF/l). The results depend of course on assumptions on the development of the price of conventional gasoline.

BFE/EWG (2004) also studies the costs of production of bio-diesel from Fischer-Tropsch process. The costs (assuming that bio-diesel is exempted from taxes) are 0.15 CHF/kWh in 2010 (conventional diesel: 0.14 CHF/kWh), in 2025 also 0.15 CHF/kWh, conventional diesel however being more expensive (about 0.20 CHF/kWh). The authors also calculate the costs in CHF/km for a VW Golf Trendline using bio-diesel in 2010 (about 0.54 CHF/km).

The authors of BFE/EWG (2004) conclude that at present ethanol is far from being competitive with gasoline. The tax on alcohol would need to be reduced compared to gasoline so as to allow bioethanol to be competitive on the vehicle fuel market. They also conclude that Fischer-Tropsch technology using biomass as a feedstock may become a competitive option.[6] It is however depending on the condition that the costs of biomass should be decreasing below its actual projection (4 cts/kWh). A major constraint for the implementation of biomass-based FT process in industrial scale would be the competition of biomass resource with other biomass energy technologies which may turn out to be less capital intensive and offer lower production costs in short to medium term. A detailed assessment of future availability and cost of biomass is necessary for an economic assessment of the FT-biofuels technology.

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[6] See e.g. www.choren.de for information on the Choren-process for producing BTL-fuel.

1.3.9 Restrictions (policies and markets)

The Swiss agricultural policy defines the current goals, which are to maintain a multifunctional agriculture with food production. It can be assumed therefore that grassland will be mostly used for animal production also in the future and that the energy production with biomass will stay marginal.

BFE/EWG (2004) sees the most relevant developments in the biomass use for energy goals in the production of heat from wood furnaces and of electricity from biomass in wood gasification and biogas plants. In 2000 the confederation stopped to subsidize wood furnaces. Now only a few cantons are granting subsidies for this kind of heating system. The confederation encourages the production of electricity from biomass. However, the plant operator has to deliver the electricity produced through the electrical power supplier.

The use of forest area is ruled by the “forest law” in Switzerland (Schweizerisches Waldgesetz), which defines the sustainable use of the Swiss forests. The total forest area is protected. Wood wastes from wood industry are already used as a raw material in other industries. In the future a competitive situation will occur between use in energy production and in material recycling.

The development of the production of biofuels has many constraints: the technology is not yet mature and the potential of biomass production in Switzerland for this application has not been studied yet. As the agriculture area isn't sufficient for the food production for the whole population and as food imports are already necessary, it cannot be expected that big areas in Switzerland can be used for energy crops like miscanthus. Forest area is however increasing, mostly in the Alpine regions.

The Swiss government plans a revision of the tax law on mineral oil. Important for further development of biofuels market in Switzerland is the foreseen tax exemption for biofuels, which would become effective on the 1.1.2007. In the same time the tax on fossil fuels would be raised, so that demand for biofuels should increase[7].

1.3.10 Import of biomass and biofuels

At the moment there is an ongoing discussion in Switzerland about the opening of the market for the importation of biofuels. Tab. 1.3 shows the major types of biofuels that might be imported to Switzerland in the near future.

Tab. 1.3 Possible bioenergy products that might be imported to Switzerland and their origin country

Product	**Countries**
Biogas	Imports improbable
Methanol	Imports improbable
RME	DE, FR, AT, IT
Biogenic waste oil	DE, FR, AT, IT
BTL	Only large-scale production makes sense. Thus imports are probable, but countries cannot be identified yet.
Ethanol, from sugar cane	BR (60% of today world production), IN, CN
Ethanol, from corn	US (40% of today world production), CN
Ethanol, from sweet sorghum	CN
ETBE	DE
Palm oil methyl ester	South and Central America, eg. BR, South-East Asia, e.g. Indonesia

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[7] see also http://www.zoll.admin.ch/d/gesetze/minoestgesetz/minoestgesetz.php

1.3.11 Summary

In Switzerland the distribution of biomass potential shows that forestry residues and wood industry by-products dominate with over 70% due to the high share of forestry in the country and the high rate of wood felling. However, forestry residues and wood by-products are currently used for energy production and in the wood processing industry. Thus only a limited market surplus is expected. There are no significant surpluses of agriculture residues. An overall increase in the use of biofuels in Switzerland is therefore only possible with the import of bioenergy products.

1.4 Characterisation of materials, energy carriers and products

The characterisation of the different products and energy carriers investigated in this project can be found in the individual chapters of part II in this report. It includes a clear characterisation of the products or fuels concerning the elemental analysis, heating value and density.

2 General methodology

The methodology for the investigation of life cycle inventory data of different unit processes has been described in detail in the methodology report of the ecoinvent project (Frischknecht et al. 2007a) and was used in this study. Thus, all unit processes are compatible with the ecoinvent datasets. For readers, who are not familiar with this methodology, it is recommended to read the methodology report before working with the unit process datasets shown in this report.

For single unit processes of this project the specific methodology for similar processes has been used. For instance, the investigation of agricultural products follows the guidelines of (Nemecek et al. 2007), the investigation of chemicals (Althaus et al. 2007a), the investigation of transport services (Spielmann et al. 2007). Biogas distribution was assessed using data from (Faist Emmenegger et al. 2003).

The following sections describe only some common conventions that are of specific relevance for the systematic investigation of bioenergy fuels, products and services in this project.

Specific methodological aspects for single unit processes are described in the subsequent chapters of part II in this report.

2.1 Time frame of the investigation

This project started in late 2004. All datasets should describe as far as possible the supply situation in Switzerland in the year 2004. This time frame is in contrast to reference year 2000 that has been chosen for the unit process datasets in ecoinvent data v1.2. Many of the processes investigated for bioenergy are emerging technologies. For a fair comparison with existing technologies it is important to consider the technological status and environmental impacts for plants working under real market conditions. Thus the most recent reference year has been chosen. If specific products are not yet introduced to the market, an assumption is made for the situation after the introduction to the market.

2.2 Plant size and assessment for emerging technologies

If plants only exist on a laboratory or pilot scale, assumptions are taken for a future scenario with a realistic plant size for a production in Switzerland. Therefore data from other countries or from small-scale plants have been used in this case. All assumptions and possible variations are documented in the EcoSpold format and in the report. Uncertainties due to such scenarios are considered in the calculation of the standard deviation.

2.3 Infrastructure for conversion processes

Data of the infrastructure of bioenergy conversion processes are rarely available. If no information is available, a rough assumption with the dataset developed for “facilities, chemical production” is used (Althaus et al. 2007a). This process is used with a standard input of 4.0 E-11 unit/kg and includes the dismantling of the plant. The pedigree matrix with (4,5,na,na,na,na) is used to determine the uncertainty for this rough estimation.

The lifetime of infrastructure of conversion processes is estimated with 50 years as a default value if specific information is not available. For the construction time 2 years are assumed.

2.4 Transports of biomass to the conversion plant

The transport distance of biomass from the point of harvest or formation to the conversion plant depends on the actual capacity of the plant and the potential of the necessary biomass resources in the surrounding area. This information is often not available. As a standard distance for the delivery of biomass from the field or the farm to the conversion plant 100 km with a “transport, lorry of 16t/CH” is used.

Swiss transport data sets are always used if the transport takes place in Switzerland.

2.5 Allocation for by-products

In several production processes for biomass fuels there are by-products. These by-products can be used for example as fodder or as a building material. In many cases it is not possible to avoid an allocation decisions because not sufficient data were available to give physical relationships for all inputs and outputs.

In general the market price of the different products has been used as an allocation criterion if no better information was available. The energy content of the products has normally not been used to derive allocation factors. Further details can be found in the detailed description of the datasets.

Tab. 2.1 Prices of several products used for economic allocation in this study

		CH	Brasil
product		price	price
		CHF	R$
biogas	kWh	0.04	
electricity, ethanol	kWh	0.10	57.5
electricity, waste incineration	kWh	0.073	
heat, waste incineration	MJ	0.09	
ethanol, 95% wt.	l	1.30	0.72
ethanol, 99.7% wt.	l	1.40	0.82
bagasse			0.04

2.6 Fuel at regional storage

Inventory data of the regional storage of liquid biofuels are consistent with the inventory data of petrol and diesel fuels (Jungbluth 2007:174). This unit process includes all transports from the processing to the filling station, the infrastructure of intermediate tanks and the filling station, fugitive emissions to air during refilling and storage operations, water emissions from run of water at the filling station.

The following standard assumptions are used if data are not available:

- 0.5 g/kg fuel are assumed as losses to air. The fugitive emissions to air have to be adapted to the fuel properties.
- Transport of fuel to the filling station is 150 km with lorry 28 t and 100 km with freight train.
- Data of electricity use, infrastructure, water use and emissions are based on the inventory of petrol (see Tab. 2.2)

If fuels are imported to Switzerland to a certain share, these transports are considered additionally.

The standard product quality for all datasets investigated for 2005 is low-sulphur diesel or petrol.

Tab. 2.2 Life cycle inventory data of fuel distribution in this project based on ecoinvent data v1.2

	Name	Location	InfrastructureProc	Unit	petrol, unleaded, at regional storage	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				kg			
product	petrol, unleaded, at regional storage	CH	0	kg	1			
technosphere	petrol, unleaded, at refinery	CH	0	kg	1.00E+0	1	1.05	(1,1,1,1,1,1); Product plus losses
	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage and filling station)
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage)
	tap water, at user	CH	0	kg	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for petrol distribution
	transport, lorry 28t	CH	0	tkm	1.50E-1	1	2.09	(4,5,na,na,na,na); Standard assumption 150km from plant to filling station
	transport, freight, rail	CH	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na); Standard assumption 100km from plant to filling station
	transport, freight, rail	RER	0	tkm		1	2.00	(,,,,,); Import of products
	transport, barge tanker	RER	0	tkm		1	2.00	(,,,,,); Import of products
	transport, crude oil pipeline, onshore	RER	0	tkm		1	1.05	(,,,,,); Import of products
	regional distribution, oil products	RER	1	unit	2.78E-10	1	3.06	(3,na,1,3,3,na); Average data for petrol station
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	1	1.25	(2,4,1,3,3,3); Used water
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	1	1.40	(4,5,3,3,3,na); Treatment of rainwater with pollutants
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	1	1.25	(2,4,1,3,3,3); Environmental report for wastes
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1	1.27	(2,4,3,3,3,3); Sludge from storage, environmental report and literature
emission air, high population density	Heat, waste	-	-	MJ	2.41E-2	1	1.14	(2,4,1,3,1,3); Calculation with electricity use
	Benzene	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Benzene, ethyl-	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Hexane	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Hydrocarbons, aliphatic, unsaturated	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Hydrocarbons, aromatic	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Methane, fossil	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	t-Butyl methyl ether	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Toluene	-	-	kg		1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties

2.7 Energy resources

The demand for biogenic energy resources is considered for all agricultural and forestry products with an input of “Energy, gross calorific value, in biomass” at the first stage of production.

This flow is not included in the investigation of secondary resources, by-products and wastes that do not bear any burdens from the upstream processes or the first life cycle. Thus, products from such biomass resources do not bear the burden of a direct use of biogenic energy resource.[8] Their actual demand for energy resources might be therefore lower than their actual energy content. This is consistent with other inventories, e.g. of cement where energy inputs from secondary resources such as waste types are not accounted for.

2.8 Reference unit of products

If not stated otherwise all information on gases is referred to the standard unit “cubic metre at normal conditions” or Nm^3. Normal conditions are a temperature of 273.15 K or 0°C and a pressure of P= 1.01325 10E5 Pa. The according volume is $V_{molar} = 0.022414\ m^3/mol$.

Please note that Nm^3 might mean different standard conditions depending on the standard used, e.g. T = 0°C = 273,15 K (DIN 1343) or T = 15°C (ISO 2533)[9]!

Some inventories for chemicals are investigated for the mass of pure chemical with a given degree of purity. Thus “ethanol, 95% in H2O, from whey, at fermentation plant” means on kilogram of pure ethanol with a purity of 95% mass percent (plus 0.053 kg of water). Thus in total the datasets refers to 1.053 kg of ethanol 95% in water. This total weight has to be considered in the calculations for transport processes.

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[8] This is not consistent e.g. with the Swiss energy statistics where energy from waste is accounted for (BFE 2000).

[9] http://normkubikmeter.lexikon.fluessiggas.net/

2.9 Biogenic carbon balance

So far different solutions have been used in the ecoinvent database to allocate the biogenic carbon content and biogenic CO2- emissions to different products with a low or unknown economic value (Doka 2007; Nemecek et al. 2007; Werner et al. 2007). Common for most of these solutions is the maintenance of a correct carbon balance even if other elementary flows are allocated according to economic properties. For agricultural products the allocation factors have been calculated according to the carbon content of the allocated co-products. For wood products a virtual allocation correction process has been introduced in order to correct the carbon balance for products with a low economic value.

With the start of the bioenergy project these different approaches have been analysed. The approach used in the bioenergy project is based on most of the models used in ecoinvent data v1.2. It has the following basic principles for all types of processes and products:

- For each product and process the biogenic and fossil C-content is reported and calculated correctly.
- For each process all functions (products and services) are taken into account. There are no hidden zero allocations to certain products or services with low or no economic value. The user can change allocation factors e.g. for changes in the revenue structure.
- For several intermediate products of the modelling prices are not available or might be quite unsure. The resulting C-balance has been modelled in all cases according to the defined product properties. There are no inconsistencies due to close to zero prices. Thus no escalating change of the C-balance can be observed if the price changes from nearby zero to zero due to the use of a cut-off approach.
- The approach fully avoids the modelling of virtual processes, which are so used only for wood products in order to maintain a correct carbon balance for products with no or low economic value (Werner et al. 2007).

A correct carbon balance should be maintained for all unit processes in the database. This means:

Input of carbon = Output of carbon

This means that the uptake of carbon during plant growing (carbon dioxide, in air) plus all inputs of biogenic carbon with pre-products minus biogenic carbon emissions (e.g. CO_2, CH_4 and CO) should equal the biogenic carbon content of the biofuel or the product after all calculations and allocations have been done. Thus the following equatation is given for each unit or multi-output process:

$$C_{\text{in,resource}} + C_{\text{in,pre-product}} = C_{\text{out, emissions}} + C_{\text{out, process-output}}$$

$C_{\text{in,resource}}$ = Carbon dioxide, in air (EcoSpold InputGroup = 4)

$C_{\text{in,pre-product}}$ = all biogenic carbon content of inputs with technosphere processes (InputGroup = 5)

$C_{\text{out, emissions}}$ = carbon content of biogenic air emissions of CO_2, CH_4, CO, NMVOC and carbon emissions to water (e.g. TOC) (OutputGroup = 4)[10]

$C_{\text{out, process-output}}$ = carbon content of outputs with technosphere processes, (OutputGroup = 0 or 2)

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[10] Biogenic carbon emissions others than CO_2, CH_4 and CO are disregarded in some cases were the CO_2-emission is based on pure mathematical calculation. Normally the influence of such deviation for the results is quite small.

Three different types of unit process outputs (products and services) can be distinguished:

1.) Electricity, heat, transport services, etc.

$C_{out,\ process\text{-}output} = 0$ (There is no material output with a C-content from such processes).

➔ $C_{in,resource} + C_{in,pre\text{-}product} = C_{out,\ emissions}$

2.) Materials, fuels, etc.

$C_{out,\ process\text{-}output} > 0$ (the C-content is equal the carbon actually bound in the product)

➔ $C_{in,resource} + C_{in,pre\text{-}product} = C_{out,\ emissions} + C_{out,\ process\text{-}output}$

3.) Waste treatment services. Waste treatment services do not have a direct link to the production of the treated product. The emissions during waste treatment should equal the carbon content of the product that is brought to waste treatment. If the same amount of the product and the waste treatment service is used in a process the resulting carbon balance should be zero. Thus the following equatation is true:

C-content(product to be treated, but not part of the unit process) + $C_{out,\ process\text{-}output} = 0$

➔ $C_{out,\ process\text{-}output} = -$ C-content(product to be treated)

➔ $C_{out,\ emissions} - C_{in,resource} - C_{in,pre\text{-}product} =$ C-content(product to be treated)

In most cases with $C_{in,resource} = C_{in,pre\text{-}product} = 0$

➔ $C_{out,\ emissions} =$ C-content(product to be treated) $= - C_{out,\ process\text{-}output}$

4.) A combination of different types of basic processes in one multi-output processes is possible. In this case the according equatation have to be fulfilled for each allocated product. The total for the multi-output process should equal the sum of the correct balances for the single outputs (services and products).

The input and output flows of biomass carbon are discussed for the individual process stages. The carbon content of all products and by-products is stated in order to follow up this balance.

Biogenic NMVOC emissions to air and carbon emissions to water (TOC – Total Organic Carbon) are not considered in the balance, if the CO_2 emission is calculated with fuel properties, because they are neither accounted for in the calculations for the climate change effects in the LCIA.[11]

The uptake of “Carbon dioxide, in air” is inventoried for all agricultural and forestry products at the beginning of the life cycle. This flow is also included in the inventory of secondary resources and by-products at the first stage of conversion to a biofuel. Due to budget restriction it was not possible to inventory the full first life cycle of such by-products, e.g. whey from milk processing (see Fig. 2.1).

The economic value of such by-products and secondary resources is not often not known. They do normally have a low or no economic value. All economic inputs from the first life cycle are thus allocated to the main products (in this case milk, for example). Thus, for the production of such biogenic wastes all inputs from the first life cycle can be neglected with the only exception of the carbon uptake during plant growing. For these biofuels the input of carbon dioxide at the beginning of their life cycle equals the emissions during conversion and combustion. This is necessary in order to achieve a neutral

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[11] This is in line with the approach taken for combustion processes using fossil fuels were the CO_2 emissions is also calculated from the carbon content of the fuel.

carbon balance while assessing environmental impacts according to the old implementation rules for greenhouse gas emissions in the database (Frischknecht et al. 2004). With the new implementation without accounting for biogenic CO_2 uptake and emissions this is normally not an issue (Frischknecht et al. 2007b)

For most of the unit processes it was necessary to use calculated CO_2 emissions (instead of measurements), a calculated input of the biomass, the biofuel input or the carbon resource in order to achieve a correct carbon balance. In contrast other emissions like CO, CH_4 and NMVOC are based on measurements.

For multi-output processes it was necessary to adapt the allocation factors for CO_2, biomass or biofuel input in order to achieve a correct balancing. Thus these factors might deviate from the factors used for all other input and output flows.

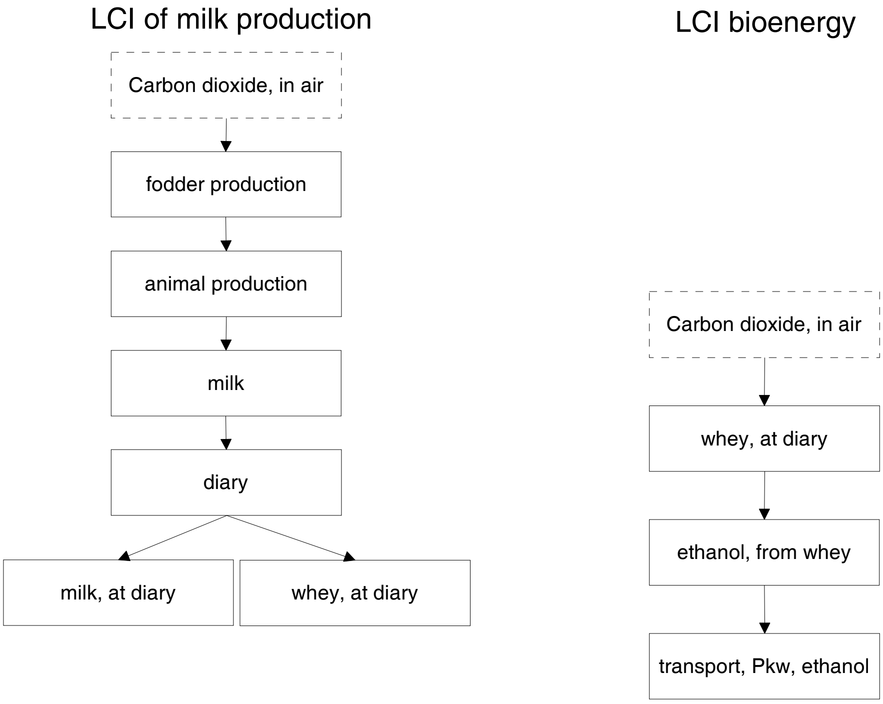

Fig. 2.1 Example for estimating a correct carbon balance for by-products with no economic value coming from a life cycle not investigated so far in the database

Tab. 2.3 shows a fictive example for the calculation of a correct carbon balance in a unit process with different inputs and outputs. The columns M and N show the inputs and outputs with each elementary flow while in the last three rows there is a calculation for the total balance. Carbon dioxide emissions are calculated as the balance of other inputs and outputs.

Tab. 2.3 Fictive example for the calculation of a correct carbon balance in a normal unit process

	B	D	E	F	G	J	K	L	M	N
3	Explanations	Input-Group	Output-Group	Name	Location	Infrastructure-Process	Unit	ethanol, 95% in H2O, from grass, at fermentation plant	biogenic carbon content in elementary flow	biogenic carbon balance
4				Location				CH		
5				InfrastructureProcess				0		
6				Unit				kg	kg	kg
7	Technosphere	5		grass from meadow intensive IP, at field	CH	0	kg	5.0E-1	0.45	0.225
8		5		grass from natural meadow intensive IP, at field	CH	0	kg	1.0E+0	0.45	0.450
9		5		grass from natural meadow extensive organic, at field	CH	0	kg	1.0E+0	0.45	0.450
10		5		transport, lorry 16t	CH	0	tkm	1.0E-1	-	-
11		5		electricity, medium voltage, at grid	CH	0	kWh	4.6E-2	-	-
12		5		heat, unspecific, in chemical plant	RER	0	MJ	6.0E-1	-	-
13		5		ethanol fermentation plant	CH	1	unit	1.4E-11	-	-
14			4	Carbon dioxide, biogenic			kg	2.1E+0	*0.27*	*0.563*
15			4	Carbon monoxide, biogenic			kg	1.0E-2	0.43	0.004
16			4	Methane, biogenic			kg	5.0E-2	0.75	0.038
17			4	Heat, waste			MJ	1.6E-1	-	-
18	Outputs		0	ethanol, 95% in H2O, from grass, at fermentation plant	CH	0	kg	1.0E+0	0.52	0.520
19										
20	Calculation			$C_{in,pre-product}$			kg			1.125
21				$C_{out, emissions}$			kg			0.042
22				$C_{out, process-output}$			kg			0.520
23				$C_{out, emissions, CO2}$ (calculated)			kg			0.563
24				Input - Output			kg			-

The following table shows a fictive example for the calculation of a correct carbon balance in a multi-output process with different inputs and outputs. The columns S and T show the inputs and outputs with each elementary flow while in the last three rows there is a calculation for the total balance. Total carbon dioxide emissions are calculated as the balance of other inputs and outputs. Allocation factors for carbon dioxide, biogenic are based on a correct input-output balance for the three couple products.

Tab. 2.4 Fictive example for the calculation of a correct carbon balance in a multi-output process

	B	D	E	F	G	J	K	L	P	Q	R	S	T
3	Explanations	Input-Group	Output-Group	Name	Location	Infrastructure-Process	Unit	grass , to fermentation	ethanol, 95% in H2O, from grass, at fermentation plant	grass fibres, at fermentation	proteins from grass, at fermentation	biogenic carbon content in elementary flow	biogenic carbon balance
4				Location				CH	CH	CH	CH		
5				InfrastructureProcess				0	0	0	0		
6				Unit				kg	kg	kg	kg	kg	kg
7	Inputs	5		grass from meadow intensive IP, at field	CH	0	kg	3.2E-1	20.0	45.0	35.0	0.45	0.146
8		5		grass from natural meadow intensive IP, at field	CH	0	kg	6.2E-1	20.0	45.0	35.0	0.45	0.277
9		5		grass from natural meadow extensive organic, at field	CH	0	kg	6.1E-2	20.0	45.0	35.0	0.45	0.027
10	Technosphere	5		transport, lorry 16t	CH	0	tkm	1.0E-1	20.0	45.0	35.0	-	-
11		5		electricity, medium voltage, at grid	CH	0	kWh	4.6E-2	20.0	45.0	35.0	-	-
12		5		heat, unspecific, in chemical plant	RER	0	MJ	6.0E-1	20.0	45.0	35.0	-	-
13		5		ethanol fermentation plant	CH	1	unit	1.4E-11	20.0	45.0	35.0	-	-
14	air, high population density		4	Carbon dioxide, biogenic			kg	1.3E+0	19.4	46.9	33.7	*0.27*	*0.354*
15			4	Carbon monoxide, biogenic			kg	1.0E-2	20.0	45.0	35.0	0.43	0.004
16			4	Methane, biogenic			kg	5.0E-2	20.0	45.0	35.0	0.75	0.038
17			4	Heat, waste			MJ	1.6E-1	20.0	45.0	35.0	-	-
18	Outputs		2	ethanol, 95% in H2O, from grass, at fermentation plant	CH	0	kg	2.5E-2	100.0			0.52	0.013
19			2	grass fibres, at fermentation	CH	0	kg	4.0E-2		100.0		0.45	0.018
20			2	proteins from grass, at fermentation	CH	0	kg	5.2E-2			100.0	0.45	0.024
21													
22	Calculation for biogenic carbon			$C_{in,pre-product}$			kg	2.2E-3	9.0E-2	2.0E-1	1.6E-1		0.450
23				$C_{out, emissions}$			kg	1.9E-5	8.4E-3	1.9E-2	1.5E-2		0.042
24				$C_{out, process-output}$			kg	2.3E-5	1.3E-2	1.8E-2	2.4E-2		0.055
25				$C_{out, emissions, CO2}$ (calculated)			kg	2.1E-3	6.8E-2	1.7E-1	1.2E-1		0.354
26				Input - Output			kg	-	-	-	-		-

Even with these refined calculation procedures some small deviations from a fully correct carbon balance are possible e.g. due to rounding errors or neglecting of water pollutants in the balance. Such deviations are tolerated if they amount to less than about 1 $^{0}/_{00}$ of the carbon flow with the production process.

2.10 Inventories for felling of primary forests

2.10.1 Introduction

Several aspects of carbon modelling have to be considered for the unsustainable use or deforestation of primary tropical forests and its following transformation to agricultural or forestry land.

Due to the initial felling, carbon dioxide is released from burning or degradation of unused biomass. Later on carbon dioxide bound in the wood is released after its use. Thus it should be considered as a CO_2- release.

A second source of CO_2-emissions is the release of carbon bound in the soil. This is degraded after the transformation i.e. to agricultural land.

These emissions and resource uses need to be allocated between the initial production of wood from the forest and subsequent transformation to agricultural land.

The felling of primary forests might also reduce methane and other emission occurring naturally (Lowe 2006). Such reductions of emissions occurring prior to the process of interest are generally not accounted for according to the ecoinvent methodology.

A change of carbon content in soils or organic matter above ground occurs also for all other types of land transformation, e.g. transformation from meadow to arable land. So far these changes have not been considered in ecoinvent data. They are normally of much less importance than the transformation of primary forests to arable land. Thus, they are also not taken into account for the inventories elaborated in this report.

2.10.2 Methodology

The inventory modelling starts with the first felling action. The uptake of CO_2 does not take place within the temporal system boundaries of the process. The uptake already took place before the first actions like building of streets or felling have been started. Thus, the existing elementary flow "Carbon dioxide, in air" is not inventoried for the carbon contents of wood and soil.

For analytical reasons it is favourable to record the non-renewable carbon bound in wood and soil with new elementary flows. Also the energy content of the wood from the primary forest is recorded with a separate elementary flow. Thus it is possible to make latter on detailed analysis with the data. The following two new elementary flows are used for the extraction of wood and for the degradation of carbon bound in soil:

Wood, primary forest, standing
Carbon, in organic matter, in soil
Energy, gross calorific value, in biomass, primary forest

All CO_2 emissions due to land transformation from wood burning and degradation of carbon bound in soil are recorded with a new type of emissions. The basic uncertainty for this elementary flow is estimated to be relative high (1.4). The separate elementary flow makes it possible to calculate different scenarios for the impact assessment of these specific type of emissions.

Carbon dioxide, land transformation

For transformation for tropical forest to agricultural land the changes for the reference plantation period are recorded. The full land transformation is allocated to the use of land for agriculture. This is the same methodological approach as used for other agricultural products (Nemecek et al. 2007). Land transformation and occupation are recorded according to existing guidelines with new elementary flows:

Occupation, tropical rain forest
Transformation, from tropical rain forest
Transformation, to tropical rain forest

The emissions must be allocated among first initial felling with the production of wood and the following use as agricultural or forestry land. Therefore a multi-output dataset is inventoried. First, the land is transformed to "forest, clear-cutting". If no better information is available all carbon dioxide releases from burning of wood and degradation of carbon content bound in soil are allocated to the use of the land for agriculture or forestry.

The further details are elaborated in the inventory analysis of such processes.

2.11 New elementary flows

The following new elementary flows have been used in the database. All LCIA methods have to be complemented by the users of the datasets investigated in this project.

Tab. 2.5 New elementary flow for resources used for this project

Name	Category	SubCategory	Formula	Unit	CAS
Occupation, tropical rain forest	resource	land	CORINE not known	m2a	
Transformation, from tropical rain forest	resource	land	CORINE not known	m2	
Transformation, to tropical rain forest	resource	land	CORINE not known	m2	
Wood, primary forest, standing	resource	biotic		m3	
Carbon, in organic matter, in soil	resource	in ground	C	kg	007440-44-0
Energy, gross calorific value, in biomass, primary forest	resource	biotic		MJ	

Tab. 2.6 New elementary flow for emissions to agricultural soil used for this project

Name	Category	SubCategory	Formula	Unit	CAS
Aldrin	soil	agricultural	C12H8Cl6	kg	000309-00-2
Acetamide	soil	agricultural	CH3CONH2	kg	000060-35-5
Acetochlor	soil	agricultural	C14H20ClNO2	kg	034256-82-1
Alachlor	soil	agricultural	C14H20ClNO2	kg	015972-60-8
Azoxystrobin	soil	agricultural	C22H17N3O5	kg	131860-33-8
Benomyl	soil	agricultural	C14H18N4O3	kg	017804-35-2
Carbufuran	soil	agricultural	C12H15NO3	kg	001563-66-2
Chlorimuron-ethyl	soil	agricultural	C15H15ClN4O6S	kg	090982-32-4
Cinidon-Ethyl	soil	agricultural	C19H17Cl2NO4	kg	142891-20-1
Clethodim	soil	agricultural	C17H26ClNO3S	kg	099129-21-2
Cloransulam-methyl	soil	agricultural	C15H13ClFN5O5S	kg	147150-35-4
Cyfluthrin	soil	agricultural	C22H18Cl2FNO3	kg	068359-37-5
Dichlorprop-P	soil	agricultural	C9H8Cl2O3	kg	015165-67-0
Diflubensuron	soil	agricultural	C14H9ClF2N2O2	kg	035367-38-5
Diflufenzopyr-sodium	soil	agricultural	C15H11F2N4NaO3	kg	109293-98-3
Dimethachlor	soil	agricultural	C13H18ClNO2	kg	050563-36-5
Dimethoate	soil	agricultural	C5H12NO3PS2	kg	000060-51-5
Dithianon	soil	agricultural	C14H4N2O2S2	kg	003347-22-6
Endosulfan	soil	agricultural	C9H6Cl6O3S	kg	000115-29-7
Esfenvalerate	soil	agricultural	C25H22ClNO3	kg	066230-04-4
Fenbuconazol	soil	agricultural	C19H17ClN4	kg	114369-43-6
Fenoxaprop	soil	agricultural	C16H12ClNO5	kg	095617-09-7
Fipronil	soil	agricultural	C12H4Cl2F6N4OS	kg	120068-37-3
Flumetsulam	soil	agricultural	C12H9F2N5O2S	kg	098967-40-9
Flumioxazin	soil	agricultural	C19H15FN2O4	kg	103361-09-7
Fluquinconazole	soil	agricultural	C16H8Cl2FN5O	kg	136426-54-5
Flurtamone	soil	agricultural	C18H14F3NO2	kg	096525-23-4
Fomesafen	soil	agricultural	C15H10ClF3N2O6S	kg	072178-02-0
Foramsulfuron	soil	agricultural	C17H20N6O7S	kg	173159-57-4
Imazamox	soil	agricultural	C15H19N3O4	kg	114311-32-9
Imazapyr	soil	agricultural	C13H15N3O3	kg	081334-34-1
Imazethapyr	soil	agricultural	C15H19N3O3	kg	081335-77-5
Iodosulfuron	soil	agricultural	C13H12IN5O6S	kg	185119-76-0
Iprodion	soil	agricultural	C13H13Cl2N3O3	kg	036734-19-7
Isoxaflutole	soil	agricultural	C15H12F3NO4S	kg	141112-29-0
Kresoxim-methyl	soil	agricultural	C18H19NO4	kg	143390-89-0
Mefenpyr	soil	agricultural	C12H10Cl2N2O4	kg	135591-00-3
Mesotrione	soil	agricultural	C14H13NO7S	kg	104206-82-8
Monocrotophos	soil	agricultural	C7H14NO5P	kg	006923-22-4
Oxydemeton-methyl	soil	agricultural	C6H15O4PS2	kg	000301-12-2
Paraquat	soil	agricultural	C12H14N2	kg	004685-14-7
Parathion	soil	agricultural	C10H14NO5PS	kg	000056-38-2
Permethrin	soil	agricultural	C21H20Cl2O3	kg	052645-53-1
Primisulfuron	soil	agricultural	C14H10F4N4O7S	kg	113036-87-6
Prosulfuron	soil	agricultural	C15H16F3N5O4S	kg	094125-34-5
Quinmerac	soil	agricultural	C11H8ClNO2	kg	090717-03-6
Quizalofop-P	soil	agricultural	C17H13ClN2O4	kg	094051-08-8
Spiroxamine	soil	agricultural	C18H35NO2	kg	118134-30-8
Sulfentrazone	soil	agricultural	C11H10Cl2F2N4O3	kg	122836-35-5
Sulfosate	soil	agricultural	C6H16NO5PS	kg	081591-81-3
tau-Fluvalinate	soil	agricultural	C26H22ClF3N2O3	kg	102851-06-9
Tebupirimphos	soil	agricultural	C13H23N2O3PS	kg	096182-53-5
Tefluthrin	soil	agricultural	C17H14ClF7O2	kg	079538-32-2
Thiophanat-methyl	soil	agricultural	C12H14N4O4S2	kg	023564-05-8
Thiram	soil	agricultural	C6H12N2S4	kg	000137-26-8
Triadimenol	soil	agricultural	C14H18ClN3O2	kg	055219-65-3
Tribenuron	soil	agricultural	C14H15N5O6S	kg	106040-48-6
Vinclozolin	soil	agricultural	C12H9Cl2NO3	kg	050471-44-8

Tab. 2.7 New elementary flow for emissions to air used for this project

Name	Category	SubCategory	Formula	Unit	CAS
Carbon dioxide, land transformation	air	high population density	CO2	kg	000124-38-9
Carbon dioxide, land transformation	air	low population density	CO2	kg	000124-38-9
Carbon dioxide, land transformation	air	low population density, long-term	CO2	kg	000124-38-9
Carbon dioxide, land transformation	air	lower stratosphere + upper tropospher	CO2	kg	000124-38-9
Carbon dioxide, land transformation	air	unspecified	CO2	kg	000124-38-9
Isoprene	air	high population density	C5H8	kg	000078-79-5
Isoprene	air	low population density	C5H8	kg	000078-79-5
Isoprene	air	low population density, long-term	C5H8	kg	000078-79-5
Isoprene	air	lower stratosphere + upper tropospher	C5H8	kg	000078-79-5
Isoprene	air	unspecified	C5H8	kg	000078-79-5
Terpenes	air	high population density	C10H16	kg	068956-56-9
Terpenes	air	low population density	C10H16	kg	068956-56-9
Terpenes	air	low population density, long-term	C10H16	kg	068956-56-9
Terpenes	air	lower stratosphere + upper tropospher	C10H16	kg	068956-56-9
Terpenes	air	unspecified	C10H16	kg	068956-56-9
Formic acid	air	high population density	CH2O2	kg	000064-18-6
Formic acid	air	low population density	CH2O2	kg	000064-18-6
Formic acid	air	low population density, long-term	CH2O2	kg	000064-18-6
Formic acid	air	lower stratosphere + upper tropospher	CH2O2	kg	000064-18-6
Formic acid	air	unspecified	CH2O2	kg	000064-18-6
Furan	air	high population density	C4H4O	kg	000110-00-9
Furan	air	low population density	C4H4O	kg	000110-00-9
Furan	air	low population density, long-term	C4H4O	kg	000110-00-9
Furan	air	lower stratosphere + upper tropospher	C4H4O	kg	000110-00-9
Furan	air	unspecified	C4H4O	kg	000110-00-9
Acetonitrile	air	high population density	C2H3N	kg	000075-05-8
Acetonitrile	air	low population density	C2H3N	kg	000075-05-8
Acetonitrile	air	low population density, long-term	C2H3N	kg	000075-05-8
Acetonitrile	air	lower stratosphere + upper tropospher	C2H3N	kg	000075-05-8
Acetonitrile	air	unspecified	C2H3N	kg	000075-05-8

2.12 Air emissions

Generally the sub-category “high population density” is used for all emissions to air from conversion processes. For other types of processes the same rules as for similar processes in ecoinvent data v1.2 are applied.

Emissions of sulphur dioxide are based on the sulphur content of the fuel.

Abbreviations

For abbreviations of country codes e.g. DE, FR, AT, IT, BR, IN, CN see the names list of the ecoinvent project.

BTL	biomass-to-liquid Treibstoff
DM	dry matter
DME	Dimethylether
dt	Dezitonnen (=100kg)
E-1	Exponential writing of figures. The information 1.2E-2 has to be read as 1.2 * 10-2 = 0.012.
ETBE	ethyl-tertiary-butyl-ether
IP	Integrated production (specific type of agricultural production in Switzerland)
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
m. o. s.	meter over sea level
Mm3	Million cubic metre

Nm^3	Norm cubic metre, volume of gases under norm conditions with temperature T = 0°C = 273,15 K (DIN 1343) **or!** T = 15°C (ISO 2533)[12] and pressure p = 101325 Pa = 101325 N/m² = 1013,25 hPa = 101,325 kPa. In this study we assume T = 0°C.
n.a.	not available
PJ	Peta Joule
RME	rape methyl ester
SME	sunflower methyl ester

References

Althaus et al. 2007a — Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A. (2007a) Life Cycle Inventories of Chemicals. ecoinvent report No. 8, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Althaus et al. 2007b — Althaus H.-J., Dinkel F., Stettler C. and F. W. (2007b) Life Cycle Inventories of Renewable Materials. Final report ecoinvent Data v2.0 No. 21. Swiss Centre for Life Cycle Inventories, Dübendorf, retrieved from: www.ecoinvent.org.

Bauer 2007 — Bauer C. (2007) Holzenergie. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.org.

BFE 2000 — BFE (2000) Schweizerische Gesamtenergiestatistik 1999. Bundesamt für Energie, Bern, CH, retrieved from: http://www.energie-schweiz.ch/bfe/de/statistik/gesamtenergie/.

BFE/EWG 2004 — BFE/EWG (2004) Potenziale zur energetischen Nutzung von Biomasse in der Schweiz: überarbeitetes und ergänztes zweites Inputpapier. Bearbeitet von der Arbeitsgemeinschaft INFRAS (Martina Blum, Bernhard Oettli, Othmar Schwank, INFRAS, Denis Bedniaguine, Edgard Gnansounou, François Golay, EPFL, Jean-Louis Hersener, Ingenieurbüro HERSENER, Urs Meier, MERITEC GmbH, Konrad Schleiss, Umwelt- und Kompostberatung). Bundesamt für Energie BFE, Ittigen, retrieved from: http://www.energie-schweiz.ch/internet/03262/index.html?lang=de.

BfS/BUWAL 2003 — BfS/BUWAL (2003) Wald und Holz in der Schweiz: Jahrbuch 2002 retrieved from: www.umwelt-schweiz.ch/buwal/de/fachgebiete/fg_wald/rubrik2/holzinfos/#sprungmarke5.

Binggeli & Guggisberg 2003 — Binggeli and Guggisberg (2003) Biomasse: Überblicksbericht zum Forschungsprogramm 2003. BfE.

Binggeli & Guggisberg 2004 — Binggeli and Guggisberg (2004) Biomasse: Überblicksbericht zum Forschungsprogramm 2004. BfE.

Dinkel 2007 — Dinkel F. (2007) Überlegungen zum Einfluss des Anbaus auf die Umweltauswirkungen von Biotreibstoffen. Carbotech for Belland AG, Basel.

---

[12] http://normkubikmeter.lexikon.fluessiggas.net/

Doka 2007	Doka G. (2007) Life Cycle Inventories of Waste Treatment Services. Final report ecoinvent v2.0 No. 13. EMPA St. Gallen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Faist Emmenegger et al. 2003	Faist Emmenegger M., Heck T. and Jungbluth N. (2003) Erdgas. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.org.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Frischknecht et al. 2007a	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007a) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Frischknecht et al. 2007b	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2007b) Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Hersener & Meier 1999	Hersener J.-L. and Meier U. (1999) Energetisch nutzbares Biomassepotential in der Schweiz sowie Stand der Nutzung in ausgewählten EU-Staaten und den USA. Im Auftrag des Bundesamtes für Energie. Bundesamt für Energie, Bern.
Jungbluth & Frischknecht 2004	Jungbluth N. and Frischknecht R. (2004) Vorstudie "LCA von Energieprodukten". Projekt Nr. 100428. ESU-services for Bundesamt für Energie and Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Uster.
Jungbluth 2007	Jungbluth N. (2007) Erdöl. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.org.
Kägi et al. 2007	Kägi T., Ruth Freiermuth-Knuchel, Nemecek T. and Gaillard G. (2007) Ökobilanz von Energiepflanzen. *In: Agrarforschung*, **14**(10), pp. 460-465, retrieved from: http://www.agrarforschung.ch/de/inh_det.php?id=1318.
Lowe 2006	Lowe D. C. (2006) Global change: A green source of surprise. *In: Nature*, **439**(12 January 2006), pp. 148-149, retrieved from: http://www.nature.com doi:10.1038/439148a.
Nemecek et al. 2007	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2007) Life Cycle Inventories of Agricultural Production Systems. ecoinvent report No. 15, v2.0. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Scheurer & Baier 2001	Scheurer K. and Baier U. (2001) Biogene Güter in der Schweiz: Massen- und Energieflüsse. Schlussbericht. Im Auftrag des Bundesamtes für Energie BFE. Hochschule Wädenswil, Wädenswil.
Spielmann et al. 2007	Spielmann M., Dones R. and Bauer C. (2007) Life Cycle Inventories of Transport Services. ecoinvent report No. 14, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Werner et al. 2007	Werner F., Althaus H.-J., Künniger T., Richter K. and Jungbluth N. (2007) Life Cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent v2.0 No. 9. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Zah et al. 2007	Zah R., Böni H., Gauch M., Hischier R., Lehmann M. and Wäger P. (2007) Ökobilanzierung von Energieprodukten: Ökologische Bewertung von Biotreibstoffen. Schlussbericht. Abteilung Technologie und Gesellschaft, Empa im Auftrag des Bundesamtes für Energie, des Bundesamtes für Umwelt und des Bundesamtes für Landwirtschaft, Bern, retrieved from: http://www.bfe.admin.ch/energie/00588/00589/00644/index.html?lang=de&msg-id=12653.

Part II

II. Life Cycle Inventories

Authors: see individual chapter

Citation:
Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J. 2007: Life Cycle Inventories of Bioenergy. ecoinvent report No. 17, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

1 Introduction to Part II

The life cycle inventories of bioenergy have been investigated in three sub-projects by different project partners. The following chapters are included in this part of the report:

- i. Swiss agricultural products
  - Grass
  - Rape seed, organic
- ii. Foreign agricultural production
  - Corn, US
  - Oil palm, MY
  - Rape seed, conventional, DE
  - Rye conventional, RER
  - Soybean, BR and US
  - Sugar cane, BR
  - Sweet sorghum, CN
- iii. Biomass conversion to fuels
  - Biogas
    - Biowaste
    - Sewage sludge
    - Liquid manure
    - Agricultural co-digestion (plants without and with coverage for methane reduction)
    - Grass
    - Whey
  - Synthetic-fuels (Methane and Methanol from wood)
  - Ethanol 95% and 99.7%
    - Swiss biomass (sugar beets, grass, whey)
    - Sugar cane in Brazil
    - Swiss biomass (sugar beet molasses, potatoes, wood) and foreign production (rye, sugar-cane molasses, corn, sweet sorghum), ETBE production with ethanol from biomass (Ethyl Tert-butyl Ether)
  - Oil-based biofuels (rape seed, palm oil, soybeans, waste cooking oil)
  - Gaseous fuels at service station (biogas and natural gas)
- iv. Transport services
  - Road transport services biofuels and alternative fuels
  - Road transport services with recent emission standards[13]
- v. Waste management services

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[13] These datasets have been investigated within this project, but they are documented in a separate ecoinvent report (Spielmann et al. 2007).

  - Incineration of Biowaste and Sewage Sludge
  - Incineration Sewage Sludge in Cement Kiln
- vi. Basic chemicals
  - Allyl chloride
  - Epichlorohydrin
  - Potassium hydroxide
  - n-Hexane
  - Synthetic glycerine
  - Allyl chloride from sieve separation of naphtha
  - Isobutene (not investigated)[14]

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[14] Isobutylene or isobutene (CAS No. 000115-11-7) is a direct refinery product. Thus, it has not been investigated. Values for “naphtha, at refinery” are used as a proxy dataset. Personal communication between Mike Chudacoff and Michael Overcash, 18.2.2005.

Part II

II.i Swiss agricultural products

Authors: see individual chapter

Citation:
Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J. 2007: Life Cycle Inventories of Bioenergy. ecoinvent report No. 17, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

2 Grass

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Review: Niels Jungbluth, ESU-services Ltd., Uster

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Abstract

The grass inventories included data refer to grass from permanent and temporary grassland in the Swiss lowland and to balled grass regarding its storage. Soil cultivation and sowing are relevant only for the temporary meadows.

For the grassland cultivation IP and organic systems with intensive and extensive production were considered. Straw, from straw areas, was included as potential grass source for the energy production. Only on intensive cultivated grassland fertilizers are applied. Pesticides against Rumex are considered for the IP production only. On the permanent meadow they are applied manually and on the temporary meadow spread before the sawing.

The data refer to the cultivation, harvest and the loading for the transport. The reference function is 1 kg dry matter of grass or straw.

2.1 Characteristic of analyzed grassland systems

Different grassland production systems including straw areas were considered for the grass production (see Tab. 2.1). The grassland systems denoted by IP refer to grass from integrated production. The grassland systems for 'organic' grass comply with the requirements for organic production (no mineral fertilizer and no pesticides). On extensive cultivated meadows contrary to the intensive meadows no fertilizer is applied. Data on the number of harvests and yields are from Walther et al. (2004). The average lifetime is fixed according to the ecoinvent quality guideline to 20 years for intensive natural meadows and 50 years for extensive natural meadows and straw areas. For the temporary meadows an average of 3 years was assumed[15].

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[15] Estimation by R. Tschachtli, LBBZ (20.5.2005): about 2-3 years for highly arable regions and 3-4 for less arable regions).

Tab. 2.1 Characteristics of grassland systems

	Number of harvest	Net yield kg DM/year	Assumed life time	Comments
grass from natural meadow intensive IP, at field	5	13'500	20	
grass from natural meadow intensive organic, at field	5	11'500	20	no mineral fertilizers and no pesticides
grass from meadow intensive IP, at field	5	13'500	3	
grass from meadow intensive, organic, at field	5	11'500	3	no mineral fertilizers and no pesticides
grass from natural meadow extensive IP, at field	1	3'000	50	no fertilization, restrictions for pesticides
grass from natural meadow extensive organic, at field	1	3'000	50	no fertilization, no pesticides
straw, from straw areas, at field	min. 1 in 3 years	2'000	50	no fertilization, no pesticides

2.1.1 Input from technosphere

Input data of different grassland systems are based mostly on input goods and machine usage as defined in the ecoinvent report No. 15 (Nemecek et al. 2004). Those inputs from technosphere include:

- Machine usage for the soil cultivation, the application of seed, fertilizers and pesticides
- Machine usage for the harvest and the balling of grass for storage
- Input goods as mineral fertilizers, pesticides and seed
- Transport of seed, mineral fertilizers, bales and pesticides

For the machine usage existing ecoinvent work processes from the ecoinvent report No. 15 (Nemecek et al. 2004) were applied unchanged. Processes defined per units or ha were normalized for the output of one kg DM by division with the yield of grass obtained (kg DM/ha and year).

Soil cultivation and seed are as in Hersener et al. (1997). Fertilizers are used for intensive production systems only. Slurry or liquid manure is mainly used. An additional single application of mineral fertilizers was considered in the IP production and of solid manure in the organic systems. The total amounts of kg N per ha and year are from recommendations of Walther et al. (2004). The portion of slurry, manure and mineral fertilizers correspond to the ecoinvent inventories of hay in the report No. 15 (Nemecek et al. 2004). Inventories of organic fertilizers include the spreading and emissions on the field. Emissions from the animal elevation and the storage of slurry and manure storage are included in the animal elevation only.

Pesticides are applied on IP grassland systems only. For the temporary meadows an application of the phenoxybutyric herbicide MCPB[16] with a field spreader was assumed to be applied before the seed, as in experimental IP farming systems in Burgrain (FAL 2004). For permanent meadows a manual application of Asulam was included for the IP production as for hay in the ecoinvent report No.15 (Nemecek et al. 2004).

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[16] 4-(4-chloro-o-tolyloxy)butyric acid

Tab. 2.2 Soil cultivation and input goods for different grassland systems

	Soil cultivation	Seed	Average application of fertilizers per year	Pesticides
grass from natural meadow intensive IP, at field	-	-	80 m^3 liquid manure (1:1) 30 kg N ammonium	0.5 l/ha*a Asulam
grass from natural meadow intensive organic, at field	-	-	60 m^3 slurry (1:2) 10 t manure	-
grass from meadow intensive IP, at field	harrowing chiselling sawing rolling	40 kg/ha	90 m^3 liquid manure (1:1) 30 kg N, ammonium nitrate	5 l MCPB/ha before seed
grass from meadow intensive organic, at field		40 kg/ha	65 m^3 slurry (1:2) 10 t manure	-
grass from natural meadow extensive IP, at field	-	-	-	None or at the most for single plants[17]
grass from natural meadow extensive organic, at field	-	-	-	-
straw, from straw areas, at field	-	-	-	-

As evaluated in the ecoinvent report No. 15 (Nemecek et al. 2004) average transport distances for the applied fertilizers, pesticides and seed were included for the transport to the regional storehouse and 15 km for the transport between the regional storehouse and the farm. Resulting transport distances for the input goods to the farm are:

- Ammonium nitrate: 900 km barge, 100 km freight, rail, 100 km lorry 28 t
- Pesticides: 15 km van <3.5t
- Seed: 15 km van <3.5t

2.1.2 Emissions to the air (N_2O, NO_x, Ammonia)

Emissions were calculated with the formula for N_2O, NO_x and Ammonia as described in the ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4). Relevant parameters are the application of fertilizers and the nitrogen fixation of the vegetation.

2.1.3 Emissions to the water (Phosphate, Phosphorus, Nitrate)

Emissions were calculated with the formula for Phosphate and Nitrate leaching to the ground water, for Phosphate and Nitrate effluent to surface water and for the Phosphorus loss with erosion as in the ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4). Emissions depend mainly on the amount and type of fertilizers applied, on the time period of the fertilization and the cultivation of soils.

2.1.4 Emissions to the soil (heavy metals, pesticides)

For the emissions to the soil an Input – Output balance was calculated for heavy metals and for the applied pesticides. The Input – Output balance of heavy metals was calculated with background data of heavy metal contents in plants, seeds and applied fertilizers (Nemecek et al. 2004, Tab. A1 to A3).

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[17] Allowed pesticides are Retsulfuron-methyl, Glyphosate, Sulfosate.

Only inputs and outputs directly related to the agricultural production were considered. As in the ecoinvent report No. 15 output through leaching, run-off and erosion - partly due to the agricultural production - were not included, due to the allocation problems (Nemecek et al. 2004).

2.1.5 CO_2-binding and solar energy in biomass

The value of CO_2-binding (1.65 kg CO_2/ kg DM) and the energy content per kilogram dry matter of harvested grass (17.9 MJ/kg DM for intensive grass and 18.9 MJ/kg DM for extensive grass) are from the inventories of hay in the ecoinvent report No. 15 (Nemecek et al. 2004, Tab. 4.7).

2.1.6 Land occupation

An average life time of 20 years was assumed for intensive natural meadows and of 50 for extensive natural meadows as in the ecoinvent report No. 15 for the production of hay on natural meadows (Nemecek et al., 2004). Straw areas listed under extensive meadows in Walter et al. (2004) were assumed to have 50 years life time. For the temporary meadows an average of 3 years was assumed[18]. The cultivation time of temporary meadows (contrary to the permanently cultivated natural meadows) is often beginning in autumn and finishing spring, resulting in two years actual cultivation time spread over three calendar years.

2.1.7 Production of grass seed, organic, at storehouse

Grass seed is produced on temporary meadows. Meadows are harvested twice before the combined harvest of about 1000 kg grass seed (Nemecek et al. 2004). For the organic seed a smaller harvest amount of 800 kg was assumed. 50% of the cultivation impacts were allocated to the beforehand harvested grass.

For organic grass seed the same processing and storage of seed was assumed as for the processing of IP grass seed in Nemecek et al. (2004). The seed proceeding includes transport, drying and storage at the regional storehouse. The drying process reduces the water content from 30% to 10%.

Biogenic CO_2 and biomass gross energy content were calculated for seeds and harvested grass. The input within seed transfered into grass was distracted in the final balance of grass to avoid a double counting.

2.1.8 Production of silage grass for storage

Baling was considered for the storage of grass dedicated for energy use. Baling was chosen as most feasible silage system for energy production. Instead of the direct loading of fresh grass on a self-loading trailer the grass is dried before the baling on the field. The water content is reduced from 85% to about 65% using for the haying and the swath a rotary windrower and a rotary tedder.

The handling and transport of silage grass is easier with baled grass than with other silage systems. For the storage of bales either on the field or on the farm no special infrastructure is required. Sanitary problems often mentioned with baling system are more relevant for the fodder quality than for the bioenergy production. An average loss of 10% dry matter was considered for the silage production (Walter et al. 2004). The production potential in Chapter 2.4 was considered for the split of input grass of different grassland cultivations systems.

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[18] Experts estimation by R. Tschachtli, LBBZ (20.5.2005): about 2-3 years for highly arable regions and 3-4 for less arable regions.

Portion of grass silage IP:

- 65% grass from natural meadow intensive IP
- 35% grass from meadow intensive IP

Portion of grass silage organic:

- 40% grass from natural meadow intensive organic
- 40% grass from natural meadow extensive organic
- 20% grass from meadow intensive organic

2.2 Characterisation of the Product

Tab. 2.3 provides general data on chemical and physical properties about the grass obtained from extensive and intensive cultivated grassland systems. Heating values for extensive and intensive produced grass and average heavy metal contents are from Nemecek et al. (2004) giving a higher energy content for extensive than intensive produced grass. A general range of carbon, hydrogen and oxygen contents of grass are given in Maier et al. (1998). From this range the values of Weidelgrass were chosen for all analysed grass types. The heating value and carbon, hydrogen and oxygen contents of straw are from Hartmann and Strehler (1995).

Whereas the data source of energy value shows a difference between intensive and extensive cultivated grass, no corresponding values were found for the further grass contents. Equal values were used therefore for the hydrogen, oxygen and carbon contents of different cultivation types, despite the different energy contents.

The values of the grass silage were calculated from the values of the silage grass mixture. For the organic silage grass from 40% extensive natural meadows, 40% intensive natural meadows and 20% temporary meadows were considered. For the IP silage grass from 35% temporary intensive meadows and 65% natural intensive meadows were considered.

Tab. 2.3 **Grass and straw data (per kg dry matter)**

		grass extensive meadows (15% DM)	grass intensive meadows (15% DM)	grassilage IP (35% DM)	grassilage organic (35% DM)	straw (15% DM)
basic unit in the database		kg DM	kg DM	kg DM	kg DM	kg DM
Lower heating value (Hu)	MJ/kg					
Lower heating value (Hu)	MJ/Nm3					
Upper heating value (Ho)	MJ/kg	18.9	17.9	17.9	18.3	17.6
Upper heating value (Ho)	MJ/Nm3	-		-	-	
Density 20°C	kg/l					
Density 20°C	kg/m3			160	160	
Oxygen	kg	0.37	0.37	0.37	0.37	0.44
Carbon, fossil	kg	0.00	0.00	0.00	0.00	0.00
Carbon, biogen	kg	0.45	0.45	0.45	0.45	0.45
Hydrogen	kg	0.05	0.05	0.05	0.05	0.06
Aluminium	mg/kg					
Arsenic	mg/kg					
Cadmium	mg/kg	0.13	0.13	0.13	0.13	0.13
Calcium	mg/kg					
Chloride	mg/kg					
Chromium	mg/kg	1.09	1.09	1.09	1.09	1.09
Copper	mg/kg	8.60	8.60	8.60	8.60	8.60
Fluoride	mg/kg					
Iron	mg/kg					
Lead	mg/kg	3.30	3.30	3.30	3.30	3.30
Magnesium	mg/kg					
Mercury	mg/kg	0.15	0.15	0.15	0.15	0.15
Nickel	mg/kg	1.68	1.68	1.68	1.68	1.68
Zinc	mg/kg	40.00	40.00	40.00	40.00	40.00
Sulphur	mg/kg	130	130	130	130	80
...	mg/kg					
CO2 Factor	kg/MJ					
CO2 Factor	kg	1.6610	1.6610	1.6610	1.6610	1.6500

2.3 Reserves and Resources

Tab. 2.4 summarizes the cultivated area and harvest potential of different grass cultivation systems based on the statistics for the year 2001 (BFE 2004). Detailed information about the areas of extensive meadows and straw areas are from the agricultural report (BLW 2004). For the intensive grassland systems a portion of organic cultivation of 10-15% was assumed, representing the average for the organic agriculture production. Extensive grassland systems were assumed to be cultivated mainly organically, as they are cultivated without fertilizers generally and only few pesticides are allowed for the treatment of single plants in the IP production.

Tab. 2.4 Grassland areas and production potentials

	Cultivation area	**% of area**	**Production potential**	**% of potential**
Intensive natural meadows (Assumption for portion of organic cultivation 10-15%)	540’400 ha	72%	2’701’785 t DM	61%
Intensive meadows (Assumption for portion of organic cultivation 10-15%)	115’600 ha	15%	1’422’528 t DM	32%
Extensive / low intensive natural meadow	89’100 ha	12%	267’177 t DM	6%
Extensive natural meadows (Assumption for portion of organic cultivation 95%)	48’700 ha			
Straw areas	6’571 ha	<1%	21’471 t DM	0.5%

2.4 Use of the Product

Biomass fibre such as grass and straw can be converted to ethanol by the conversion of cellulose, or hemi-cellulose, to starches and sugars, using enzymes and converting these sugars to ethanol (fermentation or enzymatic hydrolysis of lignocelluloses, to produce ethanol). Currently, ethanol is used as a biofuel or additive that supplements fossil fuels.

A further process to obtain a biofuel is the gasification (Fischer-Tropsch synthesis). This process involves the gasification of the biomass and subsequent reaction of the gas components to yield a liquid fuel.

2.5 Life Cycle Inventories of Individual Grassland Systems

2.5.1 Grass from meadow intensive, organic, at field

The grass is from intensive, organic production on a temporary meadow (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories for the cultivation of grass on a temporary meadow include the soil cultivation, fertilisation (cattle slurry and manure), harvest and the loading for transport.

Tab. 2.5 **Unit process raw data of grass from meadow intensive, organic, at field**

Name	Category	SubCategory	Unit	grass from meadow intensive, organic, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH			
InfrastructureProcess				0			
Unit				kg			
grass from meadow intensive, organic, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.79E+1	1	1.09	(2,1,1,3,1,3); Calculation with 17.9 MJ/kg DM (Nemecek et al. 2004, Tab. 4.7))
Carbon dioxide, in air	resource	in air	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculation with uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), which equals a total amount of 1.661 kg CO2 / kg DM grass. A correction of -0.00162 kg CO2 is considered for the input within grass seeds.
Transformation, to arable, non-irrigated	resource	land	m2	2.90E-1	1	2.05	(4,2,1,1,1,1); Calculation for one ha with a cultivation time of 3 years and a netto yield of 11'500 kg DM/year. (Experts assumption R. Tschachtli, LBBZ, 2005: cultivation time of 2-3 years in regions high arable use, 3-4 years in regions with low arable use). Assumption all area used as arable land after use as meadow.
Transformation, from arable, non-irrigated	resource	land	m2	2.03E-1	1	2.05	(4,2,1,1,1,1); Calculation for one ha with a cultivation time of 3 years and a netto yield of 11'500 kg DM/year (experts assumption R. Tschachtli, LBBZ, 2005: cultivation time of 2-3 years in regions high arable use, 3-4 years in regions with low arable use). Assumption 30% of area used as meadow before and 70% as arable land.
Transformation, from pasture and meadow, intensive	resource	land	m2	8.70E-2	1	2.05	(4,2,1,1,1,1); Calculation for one ha with a cultivation time of 3 years and a netto yield of 11'500 kg DM/year (experts assumption R. Tschachtli, LBBZ, 2005: cultivation time of 2-3 years in regions high arable use, 3-4 years in regions with low arable use). Assumption 30% of area used as meadow before and 70% as arable land.
Occupation, pasture and meadow, intensive	resource	land	m2a	8.70E-1	1	1.51	(2,2,1,1,1,3); Cultivation of a hectare over one year with a yield of 11500 kg DM per year.
Phosphate	water	ground-	kg	1.54E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	5.32E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	2.69E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Nitrate	water	ground-	kg	5.96E-3	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
tillage, harrowing, by rotary harrow	-	-	ha	2.90E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
tillage, cultivating, chiselling	-	-	ha	2.90E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
sowing	-	-	ha	2.90E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
tillage, rolling	-	-	ha	2.90E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
slurry spreading, by vacuum tanker	-	-	m3	6.09E-3	1	1.22	(2,2,1,1,3,1); Amount N corresponding to the fertilization recommendations in Walter et al. (2004). Portion of slurry and manure as for hay from natural intensive meadow in ecoinvent report No.15 (Nemecek et al. 2004). Initial fertilization of slurry before seeding considered addtionally.
solid manure loading and spreading, by hydraulic loader and spreader	-	-	kg	8.70E-1	1	1.22	(2,2,1,1,3,1); Amount N corresponding to the fertilization recommendations in Walter et al. (2004). Portion of slurry and manure as for hay from natural intensive meadow in ecoinvent report No.15 (Nemecek et al. 2004). Initial fertilization of slurry before seeding considered addtionally.
mowing, by rotary mower	-	-	ha	4.35E-4	1	1.22	(2,1,1,1,1,5); 4-6 harvests (Walter et al. 2004), 5 harvests assumed
transport, van <3.5t	-	-	tkm	1.74E-5	1	2.05	(2,2,1,1,1,5); As in Nemecek et al. (2004), transport distances for seed 15 km from storehouse
grass seed organic, at regional storehouse	-	-	kg	1.16E-3	1	1.09	(2,2,1,1,1,3); As in Hersener et al. (1997), 40 kg/ha. Assumed cultivation time 3 years
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.22	(2,2,1,1,3,1); Calculation with 120 kg/m3 and dry matter content 15% at harvest (=0.056 m3/kg DM)
Dinitrogen monoxide	air	low population dens	kg	3.41E-4	1	1.80	(2,1,3,3,4,3); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Ammonia	air	low population dens	kg	3.89E-3	1	1.58	(2,1,3,3,4,3); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low population dens	kg	7.17E-5	1	1.80	(2,1,3,3,4,3); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultural	kg	-6.50E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)

2.5.2 Grass from meadow intensive IP, at field

The grass is from intensive, integrated production on a temporary meadow (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the cultivation of grass on a temporary meadow. Included steps are soil cultivation, pesticides against Rumex, fertilisation (slurry and mineral fertilizer), harvest, loading for transport.

Tab. 2.6 Unit process raw data of grass from meadow intensive IP, at field

Name	Category	SubCategory	Unit	grass from meadow intensive IP, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location InfrastructureProcess Unit				CH 0 kg			
grass from meadow intensive IP, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.79E+1	1	1.09	(2,2,1,3,1,3); Calculation with 17.9 MJ/kg DM (Nemecek et al. 2004, Tab. 4.7))
Carbon dioxide, in air	resource	in air	kg	1.66E+0	1	1.09	(2,2,1,3,1,3); Calculation with uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), which equals a total amount of 1.661 kg CO2 / kg DM grass. A correction of -0.00132 kg CO2 is considered for the direct input within grass seed.
Transformation, to arable, non-irrigated	resource	land	m2	2.47E-1	1	2.05	(4,2,1,1,1,1); Cultivation of one ha for 3 years with a netto yield of 13'500 kg DM/year (experts assumption R. Tschachtli, LBBZ, 2005: 2-3 years cultivation in regions high arable use, 3-4 years in regions with low arable use). Assumption 30% used as meadow before and 70% as arable land.
Transformation, from arable, non-irrigated	resource	land	m2	1.73E-1	1	2.05	(4,2,1,1,1,1); Cultivation of one ha for 3 years with a netto yield of 13'500 kg DM/year (experts assumption R. Tschachtli, LBBZ, 2005: 2-3 years cultivation in regions high arable use, 3-4 years in regions with low arable use). Assumption 30% used as meadow before and 70% as arable land.
Transformation, from pasture and meadow	resource	land	m2	7.41E-2	1	2.05	(4,2,1,1,1,1); Cultivation of one ha for 3 years with a netto yield of 13'500 kg DM/year (experts assumption R. Tschachtli, LBBZ, 2005: 2-3 years cultivation in regions high arable use, 3-4 years in regions with low arable use). Assumption all area used as arable land afterwards.
Occupation, pasture and meadow, intensive	resource	land	m2a	7.41E-1	1	1.51	(2,2,1,1,1,3); Cultivation of a hectare over one year with a yield of 13500 kg DM per year.
Phosphate	water	ground-	kg	1.43E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	5.30E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	2.29E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Nitrate	water	ground-	kg	5.61E-3	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
tillage, harrowing, by rotary harrow	-	-	ha	2.47E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
tillage, cultivating, chiselling	-	-	ha	2.47E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
sowing	-	-	ha	2.47E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
tillage, rolling	-	-	ha	2.47E-5	1	1.22	(2,2,1,1,3,1); Cultivation of soil as in Hersener et al. 1997, assumed cultivation time 3 years.
slurry spreading, by vacuum tanker	-	-	m3	6.67E-3	1	1.22	(2,2,1,1,3,1); Amount N corresponding to the fertilization recommendations in Walter et al. (2004). Portion of organic and mineral fertilizer as for hay from natural intensive meadow in ecoinvent report No.15 (Nemecek et al. 2004). Initial fertilization of slurry before seeding considered addtionally.
fertilising, by broadcaster	-	-	ha	7.41E-5	1	1.22	(2,2,1,1,3,1); Yearly application of mineral fertilizer as for hay on permanent meadow in Nemecek et al. (2004)
mowing, by rotary	-	-	ha	3.70E-4	1	1.22	(2,2,1,1,3,1); 4-6 harvests (Walter et al. 2004), 5 harvests assumed
ammonium nitrate, as N, at regional storehouse	-	-	kg	2.22E-3	1	1.22	(2,2,1,1,3,1); One application of mineral fertilizer as for hay on permanent meadow in Nemecek et al. (2004)
MCPA, at regional storehouse	-	-	kg	1.23E-4	1	1.22	(2,3,1,1,1,5); 4-6 l MCPB before seeding, as in Burgrain investigations fields (FAL 52 2004). Assumed cultivation time about 3 years
transport, van <3.5t	-	-	tkm	1.67E-5	1	2.05	(2,2,1,1,1,5); As in Nemecek et al. (2004), transport distances for seed and pesticides 15 km from storehouse
grass seed IP, at regional storehouse	-	-	kg	9.88E-4	1	1.22	(2,2,1,1,1,5); As in Hersener et al. (1997), 40 kg/ha. Assumed cultivation time about 3 years.
transport, lorry 28t	-	-	tkm	6.94E-4	1	2.05	(2,2,1,1,1,5); As in Nemecek et al. (2004), transport distances for mineral fertzilizer 100 km
transport, freight, rail	-	-	tkm	6.94E-4	1	2.05	(2,2,1,1,1,5); As in Nemecek et al. (2004), transport distances for mineral fertzilizer 100 km
transport, barge	-	-	tkm	6.25E-3	1	2.05	(2,2,1,1,1,5); As in Nemecek et al. (2004), transport distances for mineral fertilizer 900 km
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.22	(2,2,1,1,3,1); Calculation with 120 kg/m3 and moisture of about 10-15% (=0.056 m3 / kg DM)
Dinitrogen monoxide	air	low population	kg	4.11E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Ammonia	air	low population	kg	5.56E-3	1	1.60	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low population	kg	8.62E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, chapter 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultural	kg	-7.61E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Chromium	soil	agricultural	kg	1.13E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Copper	soil	agricultural	kg	2.60E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Lead	soil	agricultural	kg	-2.15E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Mercury	soil	agricultural	kg	-2.99E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Nickel	soil	agricultural	kg	-2.83E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
Zinc	soil	agricultural	kg	9.11E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass, seed and fertilizers summarized in Nemecek et al. (2004)
MCPB	soil	agricultural	kg	1.23E-4	1	1.30	(2,2,1,3,1,5); Calculation input - output bilance

2.5.3 Grass from natural meadow intensive organic, at field

The grass is from intensive, organic production on a permanent meadow (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the cultivation of grass on a permanent meadow. Included steps are fertilisation (cattle slurry and manure), harvest, loading for transport.

Tab. 2.7 **Unit process raw data of grass from a natural meadow intensive organic, at field**

Name	Location	Category	SubCategory	InfrastructureProcess	Unit	grass from natural meadow intensive organic, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location						CH			
InfrastructureProcess						0			
Unit						kg			
grass from natural meadow intensive organic, at field	CH	-	-	0	kg	1			
Energy, gross calorific value, in biomass	-	resource	biotic	-	MJ	1.79E+1	1	1.09	(2,1,1,3,1,3); Calculation with 17.9 MJ/kg DM (Nemecek et al. 2004, Tab. 4.7))
Carbon dioxide, in air	-	resource	in air	-	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculation with uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), which equals a total amount of 1.661 kg CO2 / kg DM grass.
Transformation, to pasture and meadow, intensive	-	resource	land	-	m2	4.35E-2	1	2.05	(4,2,1,1,1,1); Calculation for one ha with a cultivation time of 20 years and a netto yield of 11'500 kg DM/year
Transformation, from pasture and meadow, intensive	-	resource	land	-	m2	4.35E-2	1	2.05	(4,2,1,1,1,1); Calculation for one ha with a cultivation time of 20 years and a netto yield of 11'500 kg DM/year
Occupation, pasture and meadow, intensive	-	resource	land	-	m2a	8.70E-1	1	1.51	(2,2,1,1,1,1); Cultivation of a hectare over one year with a yield of 11500 kg DM per year.
Phosphate	-	water	ground-	-	kg	1.30E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Phosphate	-	water	river	-	kg	7.34E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Phosphorus	-	water	river	-	kg	4.01E-7	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Nitrate	-	water	ground-	-	kg	1.53E-3	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
slurry spreading, by vacuum tanker	CH	-	-	0	m3	5.22E-3	1	1.22	(2,2,1,1,3,1); Portion of slurry and solid manure as for hey in ecoinvent report 15 (Nemecek et al. 2004). Total amount of N corresponds to the recommendations in
solid manure loading and spreading, by hydraulic loader and spreader	CH	-	-	0	kg	8.70E-1	1	1.22	(2,2,1,1,3,1); Portion of slurry and solid manure as for hey in ecoinvent report 15 (Nemecek et al. 2004). Total amount of N corresponds to the recommendations in
mowing, by rotary mower	CH	-	-	0	ha	4.35E-4	1	1.22	(2,2,1,1,3,1); 4-6 harvest per year (Walter et al. 2004)
fodder loading, by self-loading trailer	CH	-	-	0	m3	5.60E-2	1	1.22	(2,1,1,1,1,5); Calculation with 120 kg/m3 and moisture of about 10-15% (=0.056 m3 / kg DM)
Dinitrogen monoxide	-	air	low population d	-	kg	2.88E-4	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Ammonia	-	air	low population d	-	kg	3.75E-3	1	1.60	(2,1,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Nitrogen oxides	-	air	low population d	-	kg	6.04E-5	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report No. 15, Chapter 4.4 (Nemecek et al. 2004)
Cadmium	-	soil	agricultural	-	kg	-6.98E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Chromium	-	soil	agricultural	-	kg	1.65E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Copper	-	soil	agricultural	-	kg	1.16E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Lead	-	soil	agricultural	-	kg	-2.09E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Mercury	-	soil	agricultural	-	kg	-2.13E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Nickel	-	soil	agricultural	-	kg	-2.97E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Zinc	-	soil	agricultural	-	kg	4.87E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)

2.5.4 Grass from natural meadow intensive IP, at field

The grass is from intensive IP production on a permanent meadow (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the cultivation of grass on a permanent meadow. Included steps are fertilisation (slurry and ammonium nitrate), harvest, loading for transport.

Tab. 2.8 Unit process raw data of grass from a natural meadow intensive IP, at field

Name	Category	SubCategory	Unit	grass from natural meadow intensive IP, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH			
InfrastructureProcess				0			
Unit				kg			
grass from natural meadow intensive IP, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.79E+1	1	1.09	(2,1,1,3,1,3); Calculation with 17.9 MJ/kg DM (Nemecek et al. 2004, Tab. 4.7))
Carbon dioxide, in air	resource	in air	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculation with uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), which equals a total amount of 1.661 kg CO2 / kg DM grass.
Transformation, to pasture and meadow, intensive	resource	land	m2	3.70E-2	1	2.01	(2,2,1,1,1,3); Calculation for one ha with a cultivation time of 20 years and a netto yield of 13'500 kg DM/year
Transformation, from pasture and meadow, intensive	resource	land	m2	3.70E-2	1	2.01	(2,2,1,1,1,3); Calculation for one ha with a cultivation time of 20 years and a netto yield of 13'500 kg DM/year
Occupation, pasture and meadow, intensive	resource	land	m2a	7.41E-1	2	1.50	(1,1,1,1,1,1); Cultivation of a hectare over one year with a yield of 13500 kg DM per year.
Phosphate	water	ground-	kg	1.20E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	7.23E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	3.41E-7	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Nitrate	water	ground-	kg	1.84E-3	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
slurry spreading, by vacuum tanker	-	-	m3	5.93E-3	1	1.22	(2,2,1,1,3,1); Portion of slurry and mineral fertzilizer as for hey in ecoinvent report 15 (Nemecek et al. 2004). Total amount of N corresponds to the recommendations in Walter et al. (2004)
fertilising, by broadcaster	-	-	ha	7.41E-5	1	1.22	(2,2,1,1,3,1); One application of mineral fertilizer per year as for hay in Nemecek et al. (2004)
mowing, by rotary mower	-	-	ha	3.70E-4	1	1.22	(2,2,1,1,3,1); 5 harvests assumed, the average for intenisve meadows are 4 - 6 harvests, Walter et al. (2004)
ammonium nitrate, as N, at regional storehouse	-	-	kg	2.22E-3	1	1.22	(2,2,1,1,3,1); Portion of mineral fertzilizer as for hey in ecoinvent report 15 (Nemecek et al. 2004). Total amount of N corresponds to the recommendations in Walter et al. (2004)
[thio]carbamate-compounds, at regional storehouse	-	-	kg	1.48E-5	1	1.56	(2,2,1,1,3,1); Application of Asulam as for hey in ecoinvent report 15 (Nemecek et al. 2004). 0.5 l/gha of solution containing 0.4 kg igredient per liter.
transport, van <3.5t	-	-	tkm	5.56E-7	1	2.05	(2,2,1,1,1,5); Transport distances of pesticides and fertilizers as in Nemecek et al. (2004)
transport, lorry 28t	-	-	tkm	6.94E-4	1	2.05	(2,2,1,1,1,5); Transport distances of pesticides and fertilizers as in Nemecek et al. (2004)
transport, freight, rail	-	-	tkm	6.94E-4	1	2.05	(2,2,1,1,1,5); Transport distances of pesticides and fertilizers as in Nemecek et al. (2004)
transport, barge	-	-	tkm	6.25E-3	1	2.05	(2,2,1,1,1,5); Transport distances of pesticides and fertilizers as in Nemecek et al. (2004)
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.31	(2,2,1,3,3,5); Calculation with 120 kg/m3 and moisture of about 10-15% (=0.056 m3 / kg DM)
Dinitrogen monoxide	air	low popula	kg	3.60E-4	1	1.80	(2,1,3,3,4,3); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Ammonia	air	low popula	kg	4.97E-3	1	1.58	(2,1,3,3,4,3); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low popula	kg	7.56E-5	1	1.80	(2,1,3,3,4,3); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultural	kg	-8.22E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Chromium	soil	agricultural	kg	-1.78E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Copper	soil	agricultural	kg	1.35E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Lead	soil	agricultural	kg	-2.28E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Mercury	soil	agricultural	kg	-4.33E-8	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Nickel	soil	agricultural	kg	-4.28E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Zinc	soil	agricultural	kg	3.66E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Asulam	soil	agricultural	kg	1.48E-5	1	1.34	(4,2,3,1,1,4); Calculation input - output bilance

2.5.5 Grass from natural meadow extensive IP/organic, at field

The grass in Tab. 2.9 is from extensive IP production on a permanent meadow (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the cultivation of grass on a permanent extensive meadow. Included steps are harvest and loading for transport and the possible application of a limited list of pesticides against Rumex in the IP systems.

In the organic systems in Tab. 2.10 Rumex is removed manually without pesticides application.

Tab. 2.9 Unit process raw data of grass from a natural meadow extensive IP, at field

Name	Category	SubCategory	Unit	grass from natural meadow extensive IP, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH			
InfrastructureProcess				0			
Unit				kg			
grass from natural meadow extensive IP, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.89E+1	1	1.09	(2,1,1,3,1,3); Calculation with 18.9 MJ/kg DM energy content of grass (Nemecek et al. 2004)
Carbon dioxide, in air	resource	in air	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculated with an uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), resulting in 1.661 kg CO2 / kg
mowing, by rotary mower	-	-	ha	3.33E-4	1	1.22	(2,2,1,1,3,1); Max. 1 harvest per year, min. 1 harvest per 3 years (Walter et al. 2004). 1 harvest per year was assumed for
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.31	(2,2,1,3,3,5); Calculation with grass of about 120 kg/m3 and dry matter content of 15%
Transformation, to pasture and meadow, extensive	resource	land	m2	6.67E-2	1	2.05	(4,2,1,1,1,1); As in ecoinvent report 15 for hay, life time according the ecoinvent quality guidelines, extensiv meadow
Transformation, from pasture and meadow, extensive	resource	land	m2	6.67E-2	1	2.05	(4,2,1,1,1,1); As in ecoinvent report 15 for hay, life time according the ecoinvent quality guidelines, extensiv meadow
Occupation, pasture and meadow, extensive	resource	land	m2a	3.33E+0	1	1.51	(2,2,1,1,1,1); Calculation for one ha cultivated during one year and with a yield of 3000 kg DM/ha*a.
Phosphate	water	ground-	kg	4.58E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	1.15E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	1.54E-6	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Glyphosate	soil	agricultura	kg	3.33E-5	1	1.30	(2,2,1,1,1,5); Calculation input - output bilance
glyphosate, at regional storehouse	-	-	kg	3.33E-5	1	1.22	(2,2,1,1,1,5); Assumption application of 0.1 l Glyphosate used for single plant treatments only (allowed pesticides for
Dinitrogen monoxide	air	low popula	kg	1.65E-4	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low popula	kg	3.47E-5	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultura	kg	-1.30E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Chromium	soil	agricultura	kg	-1.09E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Copper	soil	agricultura	kg	-8.60E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Lead	soil	agricultura	kg	-3.30E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Mercury	soil	agricultura	kg	-1.50E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Nickel	soil	agricultura	kg	-1.68E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Zinc	soil	agricultura	kg	-4.00E-5	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)

Tab. 2.10 **Unit process raw data of grass from a natural meadow extensive organic, at field**

Name	Category	SubCategory	Unit	grass from natural meadow extensive IP, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH			
InfrastructureProcess				0			
Unit				kg			
grass from natural meadow extensive IP, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.89E+1	1	1.09	(2,1,1,3,1,3); Calculation with 18.9 MJ/kg DM energy content of grass (Nemecek et al. 2004)
Carbon dioxide, in air	resource	in air	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculated with an uptake of 0.453 kg carbon per kg DM grass (Maier et al. 1998), resulting in 1.661 kg CO2 / kg DM
mowing, by rotary mower	-	-	ha	3.33E-4	1	1.22	(2,2,1,1,3,1); Max. 1 harvest per year, min. 1 harvest per 3 years (Walter et al. 2004). 1 harvest per year was assumed for straw areas with use for bioenergy production. For those straw areas the use of rotary mower was assumed possible.
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.31	(2,2,1,3,3,5); Calculation with grass of about 120 kg/m3 and dry matter content of 15%
Transformation, to pasture and meadow, extensive	resource	land	m2	6.67E-2	1	2.05	(4,2,1,1,1,1); As in ecoinvent report 15 for hay, life time according the ecoinvent quality guidelines, extensiv meadow fixed at 50 years
Transformation, from pasture and meadow, extensive	resource	land	m2	6.67E-2	1	2.05	(4,2,1,1,1,1); As in ecoinvent report 15 for hay, life time according the ecoinvent quality guidelines, extensiv meadow fixed at 50 years
Occupation, pasture and meadow, extensive	resource	land	m2a	3.33E+0	1	1.51	(2,2,1,1,1,1); Calculation for one ha cultivated during one year and with a yield of 3000 kg DM/ha*a.
Phosphate	water	ground-	kg	4.58E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	1.15E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	1.54E-6	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Dinitrogen monoxide	air	low popula	kg	1.65E-4	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low popula	kg	3.47E-5	1	1.81	(2,1,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultura	kg	-1.30E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Chromium	soil	agricultura	kg	-1.09E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Copper	soil	agricultura	kg	-8.60E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Lead	soil	agricultura	kg	-3.30E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Mercury	soil	agricultura	kg	-1.50E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Nickel	soil	agricultura	kg	-1.68E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)
Zinc	soil	agricultura	kg	-4.00E-5	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass as in Nemecek et al. (2004)

2.5.6 Straw, from straw areas, at field

The straw is from straw areas (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the cultivation of straw on a straw area. Included steps are harvest and loading for transport.

Tab. 2.11 **Unit process raw data of straw, from straw areas, at field**

Name	Category	SubCategory	Unit	straw, from straw areas, at field	UncertaintyType	StandardDeviation95%	GeneralComment
Location				CH			
InfrastructureProcess				0			
Unit				kg			
straw, from straw areas, at field	-	-	kg	1			
Energy, gross calorific value, in biomass	resource	biotic	MJ	1.76E+1	1	1.09	(2,1,1,3,1,3); Calculation with 17.6 gross calorific energy content (Value for "Landschaftsheu" in Schriftenreihe "Nachwachsende Rohstoffe - Band 3 " 1995)
Carbon dioxide, in air	resource	in air	kg	1.65E+0	1	1.09	(2,1,1,3,1,3); Calculated with an uptake of 0.450 kg carbon per kg DM (value of 'Landschaftsheu', Schriftenreihe Nachwachsende Rohstoffe), resulting in 1.65 kg CO2 / kg DM
Transformation, to pasture and meadow, extensive	resource	land	m2	1.00E-1	1	2.06	(3,2,1,1,1,5); Calculation for the cultivation of one ha during one year, life time of 50 years according the ecoinvent quality guidelines
Transformation, from pasture and meadow, extensive	resource	land	m2	1.00E-1	1	2.06	(3,2,1,1,1,5); Calculation for the cultivation of one ha during one year, life time of 50 years according the ecoinvent quality guidelines
Occupation, pasture and meadow, intensive	resource	land	m2a	5.00E+0	1	1.50	(1,1,1,1,1,1); Calculation for one ha cultivated during one year with a yield of 20 dt per year.
Phosphate	water	ground-	kg	6.87E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphate	water	river	kg	1.72E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Phosphorus	water	river	kg	2.30E-6	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
mowing, by rotary mower	-	-	ha	5.00E-4	1	1.33	(3,3,1,1,3,5); Calculation with 15% dry matter content and density of about 120 kg/m3
fodder loading, by self-loading trailer	-	-	m3	5.60E-2	1	1.31	(2,2,1,3,3,5); Calculation with 15% dry matter content and density of about 120 kg/m3
Dinitrogen monoxide	air	low population density	kg	1.65E-4	1	1.84	(2,1,3,3,4,5); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Nitrogen oxides	air	low population density	kg	3.47E-5	1	1.84	(2,1,3,3,4,5); Formula as in ecoinvent report 15, Kapitel 4.4 (Nemecek et al. 2004)
Cadmium	soil	agricultural	kg	-1.30E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Chromium	soil	agricultural	kg	-1.09E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Copper	soil	agricultural	kg	-8.60E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Lead	soil	agricultural	kg	-3.30E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Mercury	soil	agricultural	kg	-1.50E-7	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Nickel	soil	agricultural	kg	-1.68E-6	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)
Zinc	soil	agricultural	kg	-4.00E-5	1	1.64	(2,1,4,3,3,4); Calculation input - output bilance using data about metal content of grass (Nemecek et al 2004)

2.5.7 Grass silage IP, at farm

The grass is from intensive IP production on natural and temporary meadows (see characteristics in Tab. 2.1 and Tab. 2.2). The inventories include the production of grass for silage from 65% natural and 35% temporary meadows. Included steps are soil cultivation, pesticides against Rumex, fertilisation (slurry and mineral fertilizer), harvest, baling, loading and transport to the farm. For the storage of bales either on the field or on the farm no special infrastructure is required.

Tab. 2.12 Unit process raw data of grass silage, IP, at farm

Name	Location	Unit	grass silage IP, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
Location			CH			
InfrastructureProcess			0			
Unit			kg			
grass silage IP, at farm	CH	kg	1			
Energy, gross calorific value, in biomass	-	MJ	1.79E+1	1	1.09	(2,2,1,3,1,3); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Carbon dioxide, in air	-	kg	1.66E+0	1	1.09	(2,2,1,3,1,3); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Transformation, to arable, non-irrigated	-	m2	9.60E-2	1	2.05	(4,2,1,1,1,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Transformation, to pasture and meadow, intensive	-	m2	2.67E-2	1	2.05	(4,2,1,1,1,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Transformation, from arable, non-irrigated	-	m2	6.72E-2	1	2.05	(4,2,1,1,1,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Transformation, from pasture and meadow, intensive	-	m2	5.56E-2	1	2.05	(4,2,1,1,1,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Occupation, pasture and meadow, intensive	-	m2a	8.23E-1	1	1.51	(2,2,1,1,1,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Phosphate	-	kg	1.42E-5	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Phosphate	-	kg	7.28E-5	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Phosphorus	-	kg	9.14E-6	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Nitrate	-	kg	3.51E-3	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
tillage, harrowing, by rotary harrow	CH	ha	9.60E-6	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
tillage, cultivating, chiselling	CH	ha	9.60E-6	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
sowing	CH	ha	9.60E-6	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
tillage, rolling	CH	ha	9.60E-6	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
slurry spreading, by vacuum tanker	CH	m3	6.87E-3	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
application of plant protection products, by field sprayer	CH	ha	2.88E-5	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
fertilising, by broadcaster	CH	ha	8.23E-5	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
mowing, by rotary mower	CH	ha	4.12E-4	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
ammonium nitrate, as N, at regional storehouse	RER	kg	2.47E-3	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
[thio]carbamate-compounds, at regional storehouse	CH	kg	1.07E-5	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
MCPA, at regional storehouse	CH	kg	4.80E-5	1	1.22	(2,2,1,1,3,1); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
transport, van <3.5t	CH	tkm	6.88E-6	1	2.05	(2,2,1,1,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
grass seed IP, at regional storehouse	CH	kg	3.74E-4	1	1.22	(2,2,1,1,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
transport, lorry 28t	CH	tkm	7.72E-4	1	2.05	(2,2,1,1,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
transport, freight, rail	RER	tkm	7.72E-4	1	2.05	(2,2,1,1,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
transport, barge	RER	tkm	6.94E-3	1	2.05	(2,2,1,1,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
transport, tractor and trailer	CH	tkm	1.50E-3	1	1.22	(2,2,1,1,1,5); Transport of bales to the farm, about 1.5 km.
swath, by rotary windrower	CH	ha	4.12E-4	1	1.22	(2,1,1,1,1,5); Short drying to reduce water content from 85% to 65% for silage production (4-5 harvest for intensive meadows, 1 harvest for extensive meadows)
haying, by rotary tedder	CH	ha	4.12E-4	1	1.22	(2,1,1,1,1,5); Short drying to reduce water content from 85% to 65% for silage production (4-5 harvest for intensive meadows, 1 harvest for extensive meadows)
baling	CH	unit	5.71E-3	1	1.31	(2,3,1,3,3,5); Calculation with 175 kg DM/m3
loading bales	CH	unit	5.71E-3	1	1.31	(2,3,1,3,3,5); Amount of bales calculated per ha with 12000-13000 kg DM/ha and 175kg DM/m3
Dinitrogen monoxide	-	kg	4.20E-4	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Ammonia	-	kg	5.75E-3	1	1.60	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Nitrogen oxides	-	kg	8.82E-5	1	1.81	(2,2,3,3,4,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Cadmium	-	kg	-8.90E-8	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Chromium	-	kg	3.12E-8	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Copper	-	kg	1.99E-6	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Lead	-	kg	-2.48E-6	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Mercury	-	kg	-4.29E-8	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Nickel	-	kg	-4.19E-7	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Zinc	-	kg	6.19E-6	1	1.64	(2,1,4,3,3,4); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
MCPB	-	kg	4.80E-5	1	1.31	(2,3,1,3,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)
Asulam	-	kg	1.07E-5	1	1.30	(2,2,1,3,1,5); Calculated from inventories of intensive natural meadows (portion 65%) and intensive temporary meadows (portion 35%)

2.5.8 Grass silage organic, at farm

The grass is from intensive organic production on natural and temporary meadows (see characteristics in Tab. 2.1 and Tab. 2.2)). The inventories include the production of grass for silage from 40% natural meadow intensive, 40% natural meadow extensive and 20% meadow intensive. Included steps are soil cultivation, fertilisation (slurry and manure), harvest, baling, loading and transport the farm. For the storage of bales either on the field or on the farm no special infrastructure is required.

Tab. 2.13 **Unit process raw data of grass silage organic, at farm**

Name	Location	Unit	grass silage organic, at farm	UncertaintyType	Standard Deviation 95%	GeneralComment
Location			CH			
InfrastructureProcess			0			
Unit			kg			
grass silage organic, at farm	CH	kg	1			
Energy, gross calorific value, in biomass	-	MJ	1.83E+1	1	1.09	(2,1,1,3,1,3); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Carbon dioxide, in air	-	kg	1.66E+0	1	1.09	(2,1,1,3,1,3); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, to arable, non-irrigated	-	m2	9.14E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, to pasture and meadow, extensive	-	m2	1.10E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, to pasture and meadow, intensive	-	m2	2.74E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, from pasture and meadow, extensive	-	m2	1.10E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, from arable, non-irrigated	-	m2	6.40E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Transformation, from pasture and meadow, intensive	-	m2	5.49E-2	1	2.05	(4,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Occupation, pasture and meadow, extensive	-	m2a	5.49E-1	1	1.51	(2,2,1,1,1,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Occupation, pasture and meadow, intensive	-	m2a	8.23E-1	1	1.62	(4,2,1,1,1,5); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Phosphate	-	kg	2.06E-5	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Phosphate	-	kg	8.20E-5	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Phosphorus	-	kg	8.98E-6	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Nitrate	-	kg	2.85E-3	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
tillage, harrowing, by rotary harrow	CH	ha	9.14E-6	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
tillage, cultivating, chiselling	CH	ha	9.14E-6	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
sowing	CH	ha	9.14E-6	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
tillage, rolling	CH	ha	9.14E-6	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
slurry spreading, by vacuum tanker	CH	m3	5.21E-3	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
solid manure loading and spreading, by hydraulic loader and spreader	CH	kg	8.23E-1	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
mowing, by rotary mower	CH	ha	4.66E-4	1	1.22	(2,2,1,1,3,1); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
transport, van <3.5t	CH	tkm	5.49E-6	1	2.05	(2,2,1,1,1,5); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
grass seed IP, at regional storehouse	CH	kg	3.66E-4	1	1.09	(2,2,1,1,1,3); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
transport, tractor and trailer	CH	tkm	1.50E-3	1	1.22	(2,2,1,1,1,5); Transport distance of bales 1.5 km from the field to the farm
swath, by rotary windrower	CH	ha	4.66E-4	1	1.22	(2,2,1,1,1,5); Short drying to reduce water content from 85% to 65% for silage production (4-5 harvest for intensive meadows, 1 harvest for extensive meadows)
haying, by rotary tedder	CH	ha	4.66E-4	1	1.22	(2,2,1,1,1,5); Short drying to reduce water content from 85% to 65% for silage production (4-5 harvest for intensive meadows, 1 harvest for extensive meadows)
baling	CH	unit	5.71E-3	1	1.31	(2,2,1,3,3,5); Calculation with 175 kg DM per unit
loading bales	CH	unit	5.71E-3	1	1.31	(2,2,1,3,3,5); Number of bales calculated with 175 kg DM per unit
Dinitrogen monoxide	-	kg	3.16E-4	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Ammonia	-	kg	3.59E-3	1	1.60	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Nitrogen oxides	-	kg	6.65E-5	1	1.81	(2,2,3,3,4,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Cadmium	-	kg	-8.60E-8	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Chromium	-	kg	9.04E-9	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Copper	-	kg	-1.24E-8	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Lead	-	kg	-2.49E-6	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Mercury	-	kg	-4.15E-8	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Nickel	-	kg	-5.21E-7	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.
Zinc	-	kg	-6.26E-7	1	1.64	(2,1,4,3,3,4); Calculation from inventories of intensive natural meadows (portion 40%), extensive natural meadows (portion 40%) and intensive temporary meadows (20%). Silage loss about 10%.

2.6 Data Quality Considerations

Tab. 2.5 to Tab. 2.13 show quality indicators for the inventories of grassland production systems. The simplified approach with a pedigree matrix has been used for calculating the standard deviation. The inventories are based on published data, statistics and recommendations. Large uncertainties exist for emissions on the field. Nevertheless in general the data quality is quite reliable.

2.7 Cumulative Results and Interpretation

2.7.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

2.7.2 Grass production

Tab. 2.14 shows selected LCI results and the cumulative energy demand for the production of grass.

Relevant for the emissions to the air and for the energy demand is mainly the machine use of different systems the emissions from combustion respectively. High energy demand and air emissions result for intensive meadows with additional machine use for the soil cultivation and for grass silage due to the extra machine use of the baling.

Effects of the intensive fertilization regime and higher leaching rates of temporary meadows after the soil cultivation are found in the emissions to the water. Emissions to the soil depend from the input – output balance of substances, which are applied with fertilizers and pesticides and extracted within the grass. The content of Cadmium for example is reduced as the output within the grass is higher than the amount in the applied fertilizers.

Extensive cultivated meadows and straw areas show generally lower emissions and energy demand. However the land occupation per unit grass of only one harvest is relatively high compared to intensive cultivated systems with much higher harvest amounts.

Tab. 2.14 **Selected LCI results and the cumulative energy demand for the grass production sytems**

		Name		grass from meadow intensive IP, at field	grass from meadow intensive, organic, at field	grass from natural meadow extensive IP, at field	grass from natural meadow extensive organic, at field	grass from natural meadow intensive IP, at field	grass from natural meadow intensive organic, at field	grass silage IP, at farm	grass silage organic, at farm
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	kg	kg	kg	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.9	0.8	0.6	0.6	0.8	0.7	1.4	1.3
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	17.9	17.9	18.9	18.9	17.9	17.9	17.9	18.3
LCI results											
resource	Land occupation	total	m2a	7.5E-1	8.8E-1	3.3E+0	3.3E+0	7.5E-1	8.8E-1	8.3E-1	1.4E+0
air	Carbon dioxide, fossil	total	kg	6.1E-2	5.6E-2	3.9E-2	3.9E-2	5.5E-2	4.9E-2	7.4E-2	6.7E-2
air	NMVOC	total	kg	1.0E-4	1.0E-4	7.3E-5	7.3E-5	9.5E-5	9.3E-5	1.4E-4	1.4E-4
air	Nitrogen oxides	total	kg	6.1E-4	5.7E-4	3.8E-4	3.7E-4	5.4E-4	5.0E-4	7.1E-4	6.5E-4
air	Sulphur dioxide	total	kg	1.0E-4	9.1E-5	6.5E-5	6.3E-5	9.1E-5	8.1E-5	1.9E-4	1.7E-4
air	Particulates, < 2.5 um	total	kg	6.2E-5	6.1E-5	4.3E-5	4.3E-5	5.5E-5	5.3E-5	6.5E-5	6.2E-5
water	BOD	total	kg	2.4E-4	2.3E-4	1.6E-4	1.6E-4	2.1E-4	2.0E-4	2.4E-4	2.2E-4
soil	Cadmium	total	kg	-7.2E-8	-6.4E-8	-1.3E-7	-1.3E-7	-8.2E-8	-6.9E-8	-8.7E-8	-8.4E-8
Further LCI results											
air	Carbon dioxide, biogenic	total	kg	-1.7E+0	-1.7E+0	-1.7E+0	-1.7E+0	-1.7E+0	-1.7E+0	-1.7E+0	-1.7E+0
air	Methane, biogenic	total	kg	8.9E-8	6.8E-8	4.9E-8	4.7E-8	7.6E-8	6.0E-8	1.3E-7	1.1E-7
air	Carbon monoxide, biogenic	total	kg	4.2E-6	4.1E-6	2.8E-6	2.7E-6	3.8E-6	3.6E-6	5.3E-6	5.0E-6
	Heat, waste	total	MJ	1.0E+0	8.8E-1	6.2E-1	6.1E-1	9.0E-1	7.8E-1	1.2E+0	1.1E+0

Abbreviations

DM	Dry Matter
LBBZ	Landwirtschaftliche Bildungs- und Beratungszentrale in Schüpfheim
LBL	Landwirtschaftliche Beratungszentrale Lindau
MCPB	Phenoxybutyric herbicide 4-(4-chloro-o-tolyloxy)butyric acid
FAT	Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik in Tänikon

Appendices: EcoSpold Meta Information

Tab. A. 1 EcoSpold Meta Information of grass from meadow intensive, organic and IP, at field

Name	grass from meadow intensive, organic, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of gras on a temporary meadow. Included steps are soil cultivation, fertilisation (cattle slurry and manure), harvest, loading for transport.
Amount	1
LocalName	Gras aus Kunstwiese intensiv Bio, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh gras from intensive organic production with 1.66 kg CO2 and 17.9 MJ per kg dry matter. The dry matter content of fresh gras is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Intensive organic production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Name	grass from meadow intensive IP, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of gras on a temporary meadow. Included steps are soil cultivation, pestizides against Rumex, fertilisation (slurry and mineral fertilizer), harvest, loading for transport.
Amount	1
LocalName	Gras aus Kunstwiese intensiv IP, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh gras from intensive IP production with 1.66 kg CO2 and 17.9 MJ per kg dry matter. The dry matter content of fresh gras is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Intensive IP production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Tab. A. 2 EcoSpold Meta Information of grass from natural meadow intensive, organic and IP, at field

Name	grass from natural meadow intensive organic, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of gras on a permanent meadow. Included steps are fertilisation (cattle slurry and manure), harvest, loading for transport.
Amount	1
LocalName	Gras aus Naturwiese intensiv Bio, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh gras from intensive organic production with 1.66 kg CO2 and 17.9 MJ per kg dry matter. The dry matter content of fresh gras is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Intensive organic production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Name	grass from natural meadow intensive IP, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of grass on a permanent meadow. Included steps are fertilisation (slurry and ammonium nitrate), harvest, loading for transport.
Amount	1
LocalName	Gras aus Naturwiese intensiv IP, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh grass from intensive IP production with 1.66 kg CO2 and 17.9 MJ per kg dry matter. The dry matter content of fresh gras is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	2000
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Intensive IP production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Tab. A. 3 EcoSpold Meta Information of grass from natural meadow extensive, organic and IP, at field

Name	grass from natural meadow extensive organic, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	68
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of grass on a permanent extensiv meadow. Included steps are harvest and loading for transport.
Amount	1
LocalName	Gras aus Naturwiese extensiv Bio, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh gras from extensive organic production with 1.66 kg CO2 and 18.9 MJ per kg dry matter. The dry matter content of fresh grass is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	2000
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m).
Text	Extenisv organic production.
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	170

Name	grass from natural meadow extensive IP, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	68
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of grass on a permanent extensiv meadow. Included steps are application of Asulam against Rumex, harvest and loading for transport.
Amount	1
LocalName	Gras aus Naturwiese extensiv IP, ab Feld
Synonyms	
GeneralComment	Refers to 1 kg dry matter of fresh grass from extensive organic production with 1.66 kg CO2 and 18.9 MJ per kg dry matter. The dry matter content of fresh gras is about 10-15%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Extensiv organic production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	170

Tab. A. 4 EcoSpold Meta Information of grass from straw, from straw areas, at field

Name	straw, from straw areas, at field
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	68
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the cultivation of straw on a straw area. Included steps are harvest and loading for transport.
Amount	1
LocalName	Streue aus Streueflächen, ab Feld
Synonyms	bedding//litter//mulch
GeneralComment	Refers to 1 kg dry matter of fresh straw from straw areas with 1.66 kg CO2 and 17.6 MJ per kg dry matter. The dry matter content of fresh straw is about 15% the density about 120 kg/m3
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to straw areas in the Swiss plateau (lowlands <700m).
Text	Extensiv organic procduction.
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	170

Tab. A. 5 EcoSpold Meta Information of grass silage, organic and IP, at farm

Name	grass silage organic, at farm
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the organic production of grass for silage from 40% natural intensive meadows, 40% natural extensive meadows and 20% temporary meadows. Included steps are soil cultivation, fertilisation (slurry and manure), harvest, baling, loading and transport to the farm.
Amount	1
LocalName	Grassilage Bio, ab Hof
Synonyms	
GeneralComment	Refers to 1 kg dry matter of grass silage from intensive organic production with 1.65 kg CO2 and an average of 18.3 MJ per kg dry matter (17.9 MJ/kg DM for intensive and 18.9 MJ/kg DM for extensive) . The dry matter content of grass silage is about 35%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m).
Text	Intensive and extnesive ogranic production.
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Name	grass silage IP, at farm
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the production of grass for silage from 65% natural and 35% temporary meadows. Included steps are soil cultivation, pestizides against Rumex, fertilisation (slurry and mineral fertilizer), harvest, baling, loading and transport to the farm.
Amount	1
LocalName	Grassilage IP, ab Hof
Synonyms	
GeneralComment	Refers to 1 kg dry matter of grass silage from intensive IP production with 1.65 kg CO2 and 17.9 MJ per kg dry matter. The dry matter content of grass silage is about 35%
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	1995
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m).
Text	Intensive IP production.
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

References

BLW 2004	BLW (2004) 2004 Agricultural Report. Elaborated by the Swiss Federal Office for Agriculture, Bern.
Nemecek et al. 2004	Nemecek et al (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch
Hersener et al. 1997	Hersener et al. (1997) Projekt Energiegras/Feldholz. Schlussbericht. Carried out at the Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik (FAT), Tänikon, ordered by the Bundesamt für Energiewirtschaft (BfE).
Hartmann und Strehler 1995	Schriftenreihe "Nachwachsende Rohstoffe" Band 3 (1995) Die Stellung der Biomasse im Vergleich zu anderen erneuerbaren Energieträger aus ökologischer, ökonomischer und technischer Sicht. Abschlussbericht für das Bundesministerium für Ernährung, Landwirtschaft und Forsten (BML). Landwirtschaftsverlag GmbH, Münster, Germany.
Maier et al. 1998	Maier, J., Dr. Vetter, R., Siegle, V., Dr. Spliethoff, H. (1998) Anbau von Energiepflanzen - Ganzpflanzengewinnung mit verschiedenen Bewertungsmethoden (ein- und mehrjährige Pflanzenarten), Schwachholzverwertung. Abschlussbericht. Ministerium Ländlicher Raum Baden-Würtemberg, Stuttgart.
Walther et al. 2001	Walther et al. (2001) Grundlagen für die Düngung im Acker- und Futterbau 2001. Eidgenössische Forschungsanstalt für Agrarökologie und Landbau, Reckenholz (FAL), Zürich.
Walther et al. 2004	Wirzhandbuch (2005) Pflanzen und Tiere. For the LBL Lindau, Wirz Verlag, Basel.
FAL 2004	FAL Reckenholz (2004) Integrierter und biologischer Anbau im Vergleich - Anbausystemversuch Burgrain. Schriftenreihe der FAL 52, Agroscope FAL Reckenholz, Zürich, CH, retrieved from: www. reckenholz.ch

3 Rape seed, organic, at farm

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Abstract

The inventory refers to organic produced rape seed in the Swiss lowland.

The inventory for organic rape seed includes data about organic production standards and their emissions to the air, water and soil recalculated for the use of slurry and manure applied. In the organic production only organic produced seed is used and no synthetic pesticides are applied.

The data refer to the cultivation, harvest, drying and transport to the farm. The reference function is 1 kg rape seed with 6% moisture.

3.1 Characteristic of rape seed organic cultivation

Organic rape seed is produced under the conditions described in Tab. 3.1. Compared to the IP production with an average netto yield of about 3'130 kg/ha (Walther et al. 2004) a lower yield of about 2'023 kg/ha is obtained in the organic production (Nemecek et al., 2005, FAL 58). The organic production systems comply with the requirements for organic production (no application of mineral fertilizers and pesticides).

Tab. 3.1 Characteristics of rape seed, organic production

	Net yield kg /ha*a	Cultivation time	Comments
rape seed, organic, at farm	2'023	About 11 months (seed in August and harvest in July of the following year)	Only organic fertilizers and no application of pesticides

3.1.1 Input from technosphere

Input data of the organic rape seed production is based mostly on working processes on the field as defined for the organic rape seed production in the FAL report 58 (Nemecek et al., 2005) and for the IP rape seed production in ecoinvent report No. 15 (Nemecek et al. 2004). The inputs from technosphere include the machine usage for the soil cultivation, the spreading of fertilizers, the harvest and the drying of grains and their transport.

For the machine usage and the transport existing work processes from the ecoinvent report No. 15 (Nemecek et al., 2004) were applied unchanged. Processes defined per units or ha were normalized for the output of one kg rape seed by division with the yield obtained (kg per ha and year).

For the applied slurry and manure only emissions of slurry and manure due to the direct application on the field are included. The total amount of slurry and manure and their data of application correspond to the data in the FAL report 58 (Nemecek et al., 2005),. Reported are slurry application in March and manure application in August.

No pesticides are applied for organic rape seeds production. A transport of 0.5 km with tractor and trailor was included for the transport to the farm and of 15 km with a van <3.5t to the storehouse.

Tab. 3.2 **Soil cultivation and input goods for the production of organic rape seed**

	Soil cultivation	Fertilization	Pesticides
rape seed, organic, at farm	Tillage: ploughing, harrowing twice, hoeing, seeding as in FAL 58 (Nemecek et al., 2005)	20 m^3 slurry in March (dilution about 1:2) 30 t manure in August	No pesticides

3.1.2 Emissions to the air (N_2O, NO_x, ammonia)

Emissions were calculated with the formula for N_2O, NO_x and Ammonia as described in the ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4). Relevant parameters are the application of fertilizers and the nitrogen fixation of the vegetation.

3.1.3 Emissions to the water (phosphate, phosphorus, nitrate)

Emissions were calculated with the formula for Phosphate and Nitrate leaching to the ground water, for Phosphate and Nitrate effluent to surface water and for the Phosphorus loss with erosion as in the ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4). Emissions depend mainly on the amount and type of fertilizers applied, on the time period of the fertilization and the cultivation of soils.

3.1.4 Emissions to the soil (heavy metals)

An Input – Output balance was calculated with background data of heavy metal contents summarized for plants, seeds and fertilizers in ecoinvent report No. 15 (see table A1 to A3, Nemecek et al. 2004).

Only inputs and outputs directly related to the agricultural production where considered. As in the ecoinvent report No. 15, output through leaching, run-off and erosion - partly due to the agricultural production - were not included, due to the allocation problems (Nemecek et al. 2004).

3.1.5 CO2-binding and solar energy in biomass of rape seed

The value for CO_2 -binding of 2.86 kg CO_2/kg DM was used as for the rape seed IP in Nemecek et al. (2004). For the energy content of rape seed the value of 31.47 MJ/kg DM was used as in Maier et al. (1998). Compared to the values given per kg dry mater the contents in stored rape seed with 6% moisture are 2.69 kg CO_2 and 29.58 MJ.

The final amount of biogenic CO_2 and biomass gross energy transferred from seed into the rape plants was distracted in the balance of rape seed cultivation to avoid a double counting (see chapter 3.1.8).

3.1.6 Land occupation of rape seed cultivation

The cultivation of winter rape starts with the seed in October and ends with the harvest in August (Walther et al. 2004), resulting in a cultivation time of about 10 to 11 months over a time period of two calendar years. It was assumed that the rape seed production is mostly part of rotation with other crops and less frequently been transformed to arable land from pasture and meadows.

3.1.7 Cold drying of rape seed

The ecoinvent process cold drying was considered for the organic rape seed to reduce the initial moisture of about 12% to 6% as for the IP rape seed in the ecoinvent report No. 15 (Nemecek et al. 2004).

3.1.8 Seed, organic, at storehouse

No special inventory was defined for the seed production of organic rape. The module "rape seed organic, at farm, CH" was used instead. To account the lower yield of the seed production a greater quantitiy of rape seed was taken, namely 1.75 kg per kg seed produced. This ratio was assumed in Nemecek et al. (2004) for IP seed considering a lower harvest amount of 1800 kg seed instead of 3150 kg. The same ratio was used also for the lower yields of organic production.

For organic rape seed the same processing and storage of seed was assumed as for the processing of IP rape seed in Nemecek et al. (2004). The seed proceeding includes transport, drying and storage at the regional storehouse.

Biogenic CO_2 and biomass gross energy content were calculated. A correction for the greater quantity of rape seed (1.75 kg per kg seed) was carried out considering the actual lower harvest amount of seed production of rape. The final amount of biogenic CO_2 and biomass gross energy transferred from seed into the rape plants was distracted in the balance of rape seed cultivation to avoid a double counting.

3.2 Characterisation of rape seed, organic

Tab. 3.3 provides general data about the rape seed obtained from intensive cultivated organic production systems. Data for the CO_2 binding and metal contents are from Nemecek et al. (2004) and for the Heating value from Maier et al. (1998).

Tab. 3.3 Organic rape seed, physical and chemical properties (per kg rape seed with 6% moisture)

		rape seed (6% moisture)
basic unit in the database		kg
Lower heating value (Hu)	MJ/kg	
Lower heating value (Hu)	MJ/Nm3	
Upper heating value (Ho)	MJ/kg	29.6
Upper heating value (Ho)	MJ/Nm3	-
Density 20°C	kg/l	
Density 20°C	kg/m3	
Oxygen	kg	
Carbon, fossil	kg	0.00
Carbon, biogen	kg	0.73
Hydrogen	kg	
Cadmium	mg/kg	1.50
Chromium	mg/kg	0.47
Copper	mg/kg	3.10
Lead	mg/kg	4.94
Mercury	mg/kg	0.09
Nickel	mg/kg	2.44
Zinc	mg/kg	45.12
Sulphur	mg/kg	46
...	mg/kg	
CO2 Factor	kg/MJ	
CO2 Factor	kg	2.69
heat, waste	MJ/MJin	
Coke residue	Gew. %	

3.3 Reserves and Resources of rape seed production

In 2003 the cultivation area of rape seed was about 16'000 ha with an average harvest of about 3.13 dt/ha (Walter et al. 2004) and a portion of about 15-20% extensive cultivated area. Only few rape seed is produced organically, the total area increased from 15 to 35 ha in the last years (<1%)[19].

3.4 Use of rape seed

Vegetable oils, such as rapeseed, can be used as a diesel fuel without further processing. However, the process of transesterification reduces the high viscosity of vegetable oil, resulting in a higher-quality fuel. In the transesterification process, vegetable oil reacts with alcohol (methanol or ethanol) in the presence of a catalyst. When rapeseed oil is the feedstock, the products of the reaction are glycerol and rapeseed methyl or ethyl ester (RME or REE). As biodiesel fuels, RME or REE can be used in pure form or in a blend with petroleum diesel. Required quality standards of RME for fuel use are defined in DIN EN 14214.

3.5 Life Cycle Inventories of rape seed, organic, at farm

Inventory refers to the production of 1 kg rape seed, organic, at farm with 6% moisture. The inventories include the soil cultivation, fertilization, harvest, cold drying and transport to the farm.

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[19] Information found 20.5.2005 on www.reckenholz.ch/doc/de/forsch/landbau/system/praxisbio.html

Tab. 3.4 Unit process of rape seed, organic, at farm

	Name	Location	Unit	rape seed, organic, at farm	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kg			
product	rape seed, organic, at farm	CH	kg	1			
resource, biotic	Energy, gross calorific value, in biomass	-	MJ	2.95E+1	1	1.14	(2,1,3,3,1,3); Energy content 31.47 MJ/kg DM (Maier et al.1998), correction for direct input within seed of -0.04402 MJ
resource, in air	Carbon dioxide, in air	-	kg	2.68E+0	1	1.09	(2,1,1,3,1,3); CO2-binding of 2.86 kg/kg DM (Nemecek et al. 2004), correction for direct input within seed of -0.00400 kg CO2/kg seed
resource, land	Occupation, arable, non-irrigated	-	m2a	4.33E+0	1	1.12	(2,2,1,1,1,1); Cultivation of winter rape seed from October to August of the following year (85-90% occupation for rape seed cultivation and 10-15% for other use)
	Transformation, from pasture and meadow, intensive	-	m2	9.89E-1	1	1.21	(2,2,1,1,1,1); Assumption 1/5 transformed from pasture and meadows
	Transformation, from arable, non-irrigated	-	m2	3.95E+0	1	1.21	(2,2,1,1,1,1); Assumption 4/5 transformed from arable land
emission water, ground-	Phosphate	-	kg	8.17E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
emission water, river	Phosphate	-	kg	3.14E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
emission water, river	Phosphorus	-	kg	9.11E-5	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
emission water, ground-	Nitrate	-	kg	4.76E-2	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
technosphere	tillage, harrowing, by spring tine harrow	CH	ha	9.89E-4	1	1.07	(2,2,1,1,1,1); Soil cultivation as in FAL 58 (Nemecek et al., 2005)
technosphere	hoeing	CH	ha	4.94E-4	1	1.07	(2,2,1,1,1,1); Soil cultivation as in FAL 58 (Nemecek et al., 2005)
technosphere	tillage, currying, by weeder	CH	ha	4.94E-4	1	1.07	(2,2,1,1,1,1); Soil cultivation as in FAL 58 (Nemecek et al., 2005)
technosphere	tillage, ploughing	CH	ha	4.94E-4	1	1.07	(2,2,1,1,1,1); Soil cultivation as in FAL 58 (Nemecek et al., 2005)
technosphere	sowing	CH	ha	4.94E-4	1	1.05	(1,1,1,1,1,1); Soil cultivation as in FAL 58 (Nemecek et al., 2005)
technosphere	combine harvesting	CH	ha	4.94E-4	1	1.22	(2,2,1,1,3,1); Harvest as for rape seed IP in Nemecek et al. (1999)
technosphere	slurry spreading, by vacuum tanker	CH	m3	9.89E-3	1	1.07	(2,1,1,1,1,1); Application of 20m3 slurry in march as in FAL 58 (Nemecek et al., 2005). Dilution to about 50 m3
	solid manure loading and spreading, by hydraulic loader and spreader	CH	kg	1.48E+1	1	1.07	(2,1,1,1,1,1); Application of 30t manure in august as in FAL 58 (Nemecek et al., 2005).
	grain drying, low temperature	CH	kg	6.81E-2	1	1.22	(2,2,1,1,3,1); Drying from about 12% to 6% water content as for rape seed IP in Nemecek et al. (2004)
	rape seed organic, at regional storehouse	CH	kg	2.72E-3	1	1.09	(2,2,1,1,1,3); Seed as in FAL 58 (Nemecek et al., 2005)
	transport, van <3.5t	CH	tkm	4.08E-5	1	2.05	(2,2,1,1,1,5); Transport distance for seed 15 km from storehouse as in Nemecek et al. (2004)
	transport, tractor and trailer	CH	tkm	5.00E-4	1	2.09	(4,1,1,1,1,5); Calculation with 0.5 km transport distance to the farm
resource, land	Transformation, to arable, non-irrigated	-	m2	4.94E+0	1	1.24	(2,1,3,3,1,3); Further use as arable land
emission air, low population density	Dinitrogen monoxide	-	kg	1.27E-3	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
emission air, low population density	Ammonia	-	kg	1.46E-2	1	1.60	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4), area spread 50%
emission air, low population density	Nitrogen oxides	-	kg	2.68E-4	1	1.81	(2,2,3,3,4,4); Formula as in ecoinvent report No. 15 (Nemecek et al. 2004, Chapter 4.4)
emission soil, agricultural	Cadmium	-	kg	-9.62E-7	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Chromium	-	kg	1.17E-5	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Copper	-	kg	7.52E-5	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Lead	-	kg	6.81E-6	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Mercury	-	kg	1.15E-6	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Nickel	-	kg	1.10E-5	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)
	Zinc	-	kg	3.35E-4	1	1.64	(2,1,4,3,3,4); Input - Output Bilance for plants, seed and fertilizers with heavy metal contents as in Nemecek et al. (2004)

3.6 Life Cycle Inventories of rape seed, organic, at storehouse

The inventory of seed refers to 1 kg rape seed, organic, at storehouse with 6% moisture. No special inventory was defined for the seed production. The module "rape seed organic, at farm, CH" was used. To account the lower yield of the seed production a greater quantity of rape seed was taken, namely 1.75 kg per kg seed produced. A correction of biogenic CO_2 and biomass gross energy was therefore necessary (distraction of CO_2 and energy content of 0.75 kg rape seed).

For organic rape seed the same processing and storage of seed was assumed as for the processing of IP rape seed in Nemecek et al. (2004). The seed proceeding includes transport, drying and storage at the regional storehouse.

Tab. 3.5 Unit process of rape seed, organic, at storehouse

	Name	Location	Unit	rape seed organic, at regional storehouse	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kg			
product	rape seed organic, at regional storehouse	CH	kg	1			
resource, land	Occupation, construction site	-	m2a	8.00E-6	1	1.51	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
	Occupation, industrial area, built up	-	m2a	2.00E-3	1	1.51	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
	Transformation, from unknown	-	m2	4.00E-6	1	2.01	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
resource, biotic	Energy, gross calorific value, in biomass	-	MJ	-2.22E+1	1	1.09	(2,2,1,1,1,3); The yield of seed production is only 1800 kg/ha compared to the average harvest amount of 3150 kg/ha. In order to use the same cultivation process despite the lower yield 1.75 kg rape seed were applied per kg seed. A distraction of the amount of energy in 0.75 kg seed was necessary.
resource, in air	Carbon dioxide, in air	-	kg	-2.02E+0	1	1.09	(2,2,1,1,1,3); The yield of seed production is only 1800 kg/ha compared to the average harvest amount of 3150 kg/ha. In order to use the same cultivation process despite the lower yield 1.75 kg rape seed were applied per kg seed. A distraction of the amount of CO2 in 0.75 kg seed was necessary.
resource, land	Transformation, to industrial area, built up	-	m2	4.00E-6	1	2.01	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
technosphere	electricity, low voltage, at grid	CH	kWh	5.80E-2	1	1.09	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
technosphere	rape seed, organic, at farm	CH	kg	1.75E+0	1	1.09	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
technosphere	transport, lorry 32t	RER	tkm	9.00E-1	1	2.01	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
emission air, high population density	Heat, waste	-	MJ	2.09E-1	1	1.09	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)
technosphere	building, multi-storey	RER	m3	2.00E-6	1	3.01	(2,2,1,1,1,3); As for rape seed IP in Nemecek et al. (2003)

3.7 Data quality considerations

Tab. 3.4 and Tab. 3.5 show data quality indicators for the inventory of rape seed production systems. The simplified approach with a pedigree matrix has been used for calculating the standard deviation. The inventory is based on published data, statistics and recommendations. Large uncertainties exist for emissions on the field. Nevertheless in general the data quality is quite reliable.

3.8 Cumulative results and interpretation

The selected LCI results and the cumulative energy demand for the organic rape seed production can be found in the database.

Relevant for the energy demand and emissions to the air is mainly the machine use with its emissions from combustion. For emissions to the soil and water the application of fertilizers is relevant. Emissions to the soil depend on the input – output balance of substances, which are applied with fertilizers and extracted within the rape plant. The content of cadmium for example is reduced with organic production, because the output within the rape seed is higher than the amount in the applied fertilizers.

Abbreviations

DM	Dry Matter
LBBZ	Landwirtschaftliche Bildungs- und Beratungszentrale in Schüpfheim
LBL	Landwirtschaftliche Beratungszentrale Lindau
FAT	Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik in Tänikon

Appendices: EcoSpold Meta Information

Tab. A. 6 EcoSpold Meta Information of rape seed organic, at farm

Name	rape seed, organic, at farm
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	The inventories include the soil cultivation, fertilization, harvest, drying and transport to the farm
Amount	1
LocalName	Raps Bio, ab Hof
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg rape seed, organic, at farm with 6% moisture. Fresh matter yield at 6 % moisture: 2023 kg/ha.
InfrastructureIncluded	1
Category	agricultural production
SubCategory	plant production
LocalCategory	Landwirtschaftliche Produktion
LocalSubCategory	Pflanzenbau
Formula	
StatisticalClassification	
CASNumber	
StartDate	2000
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m). Intensive organic production.
Text	
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from study areas, statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

Tab. A. 7 EcoSpold Meta Information of rape seed organic, at storehouse

Name	rape seed organic, at regional storehouse
Location	CH
InfrastructureProcess	0
Unit	kg
Type	1
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	69
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	Refers to 1 kg seed of rape seed (fresh weight), with a maximum water content of 6%
Amount	1
LocalName	Raps-Saatgut Bio, ab Regionallager
Synonyms	
GeneralComment	The seed produced at the farm is transported to the processing centre, treated (pre-cleaning, cleaning, eventually drying, chemical dressing (for integrated production) and bag filling), stored and afterwards transported to the regional storage centre. No data on wastewater production were available.
InfrastructureIncluded	1
Category	agricultural means of production
SubCategory	seed
LocalCategory	Landwirtschaftliche Produktionsmittel
LocalSubCategory	Saatgut
Formula	
StatisticalClassification	
CASNumber	
StartDate	2000
EndDate	2005
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Refers to a production in the Swiss plateau (lowlands <700m).
Text	Intensive organic production.
Percent	
ProductionVolume	
SamplingProcedure	Data were compiled from statistics, fertilising recommendations, documents from extension services and expert knowledge.
Extrapolations	
UncertaintyAdjustments	none
Person	68
DataPublishedIn	2
ReferenceToPublishedSource	40

References

Nemecek et al. 2004	Nemecek et al (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch
Nemecek et al. 2005	Nemececk et al. (2005) Ökobilanzierung von Anbausystemen im schweizerischen Acker- und Futterbau, Schriftenreihe der FAL 58. Acroscope FAL Reckenholz, Zürich.
Maier et al. 1998	Maier, J., Dr. Vetter, R., Siegle, V., Dr. Spliethoff, H. (1998) Anbau von Energiepflanzen - Ganzpflanzengewinnung mit verschiedenen Bewertungsmethoden (ein- und mehrjährige Pflanzenarten), Schwachholzverwertung. Abschlussbericht. Ministerium Ländlicher Raum Baden-Würtemberg, Stuttgart.
BFE 2004	BFE (2004) Potentiale zur energetischen Nutzung von Biomasse in der Schweiz (Anhang). Bundesamt für Energie BFE, 3003 Bern.
Walther et al. 2001	Walther et al. (2001) Grundlagen für die Düngung im Acker- und Futterbau 2001. Eidgenössische Forschungsanstalt für Agrarökologie und Landbau, Reckenholz (FAL), Zürich.
Walther et al. 2004	Walther et al. (2004) Wirzhandbuch 2005. Pflanzen und Tiere. For the LBL Lindau, Wirz Verlag, Basel.
FAL 2004	FAL Reckenholz (2004) Integrierter und biologischer Anbau im Vergleich - Anbausystemversuch Burgrain. Schriftenreihe der FAL 52, Agroscope FAL Reckenholz, Zürich, CH, retrieved from: www. reckenholz.ch

4 Clear cutting of primary forests

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4.1 Introduction

The inventory investigates the clear cutting of primary forest with a main focus on subsequent land use for palm oil production in Malaysia and soybean production in Brazil.

Forest and grassland conversion is the major cause for CO_2 emissions in Brazil. A total of 951 billion tonnes of CO_2 have been emitted in 1994. This equals 92.4% of the total CO_2 emissions in the country. Also other pollutants like carbon monoxide, methane, N_2O, etc. are released in important shares due to the land conversion activities (Ministry of Science and Technology 2004).

In Malaysia about 7.6 Mio. tonnes of CO_2 are released due to land conversion activities. This equals about 7.8% of the national CO_2 emissions in 1994 (Ministry Of Science- Technology And The Environment 2000).

4.2 Reserves and resources of the process

The processes have been investigated at first hand for the provision of agricultural land in Brazil and Malaysia. In Malaysia about 150000 ha/a are provided for palm fruits. In Brazil about 2 Mio. ha/a are provided for soybeans.

About 151 to 190 tonnes of carbon are bound above the ground per hectare in Malaysia and Brazil, respectively (Achard et al. 2002). The biomass has a dry weight of double this amount. From this the total amount of wood per hectare can be calculated (bottom of Tab. 4.4).

4.3 Characterisation of wood, primary forest, standing

In deforestation processes the biomass of tropical rainforests is calculated as resource "wood, primary forest, standing". The properties of the wood are given in Tab. 4.1.

Tab. 4.1 Properties of wood, primary forest, standing

Property	Value	Unit	Source
Water	0.12	kg/kg wood fm	(Brown 1997)
Carbon content	0.5	kg/kg wood fm	(Achard et al. 2002)
Carbon content	0.568	kg/kg wood dm	calculated
HHV	18.48	MJ/kg wood fm	calculated
HHV	21	MJ/kg wood dm	calculated

In Tab. 4.2 data for the wood density are given. The harvested wood has a density of 583 kg/m^3.

Tab. 4.2 Wood density in tropical rainforests by region (Brown 1997)

Region	Wood density (kg/m^3)
Central America	600
Africa	580
Southeast Asia	570
Average	**583.3**

Values for carbon bound in biomass above ground and wood per ha for several regions are given in Tab. 4.3.

Tab. 4.3 Biomass and wood per ha in tropical rainforests by region

Region	Carbon bound in biomass (t/ha)[1]	Biomass (t/ha)	Wood (m^3/ha)
Brazil	190	380	651.4
Central America	129	258	442.3
Africa	179	358	613.7
Southeast Asia	151	302	517.7

Source: 1: (Achard et al. 2002)

4.4 Use of stubbed land and wood

The clear cutting of primary forest has two functions. The first is the production of wood. The harvested wood is sold on the wood market. The second is the provision of stubbed land that can be used for agriculture, forestry, street construction, settlings or hydro power plants. Both functions are taken into account.

4.5 System characterisation

Information describing the investigated system can be found in Tab. 4.4.

Tab. 4.4 Meta Information describing the datasets for clear cutting of primary forest

ReferenceFunction	Name	clear-cutting, primary forest	clear-cutting, primary forest
Geography	Location	MY	BR
ReferenceFunction	InfrastructureProcess	0	0
ReferenceFunction	Unit	ha	ha
DataSetInformation	Type	5	5
	Version	1.0	1.0
	energyValues	0	0
	LanguageCode	en	en
	LocalLanguageCode	de	de
DataEntryBy	Person	41	41
	QualityNetwork	1	1
ReferenceFunction	DataSetRelatesToProduct	1	1
	IncludedProcesses	Resources (wood, carbon, land), land transformation, emissions from wood burning, rough estimation for machinery use.	Resources (wood, carbon, land), land transformation, emissions from wood burning, rough estimation for machinery use.
	Amount	1	1
	LocalName	Kahlschlag, Primärwald	Kahlschlag, Primärwald
	Synonyms		
	GeneralComment	Multi-output process providing the products "round wood, primary forest, clear-cutting, at forest road" and "provision, stubbed land". Emissions from wood burning and land transformation are allocated to the provision of stubbed land.	Multi-output process providing the products "round wood, primary forest, clear-cutting, at forest road" and "provision, stubbed land". Emissions from wood burning and land transformation are allocated to the provision of stubbed land.
	InfrastructureIncluded	1	1
	Category	wooden materials	wooden materials
	SubCategory	extraction	extraction
	LocalCategory	Holzbaustoffe	Holzbaustoffe
	LocalSubCategory	Gewinnung	Gewinnung
	Formula		
	StatisticalClassification		
	CASNumber		
TimePeriod	StartDate	2001	2001
	EndDate	2005	2005
	DataValidForEntirePeriod	1	1
	OtherPeriodText	Publication of data	Publication of data
Geography	Text	South-Asian primary forest.	South-American primary forest.
Technology	Text	Clear-cutting of primary forests with burning of biomass.	Clear-cutting of primary forests with burning of biomass.
Representativeness	Percent	100	100
	ProductionVolume	150000 ha/a for palm fruits	about 2 Mio. ha/a for soy beans
	SamplingProcedure	Literature data	Literature data
	Extrapolations	Rough estimation of machinery use with European forestry data. Emissions profile for tropical forest per kg of dry biomass.	Rough estimation of machinery use with European forestry data. Emissions profile for tropical forest per kg of dry biomass.
	UncertaintyAdjustments	none	none

4.6 Life cycle inventory of clear cutting primary forests

Tab. 4.5 shows the unit process raw data and data quality indicators for the inventory of clear cutting of primary forests in Brazil and Malaysia. The simplified approach with a pedigree matrix has been used for calculating the standard deviation. The inventory takes into account the use of machinery for felling of trees, resource uses, emissions due to burning of biomass and the land transformation issue.

It is presumed that 20% of the above ground biomass is burned, 70% is left as slash, 8% is used for wood products and 2% remains as elemental carbon in biomass (data for Brazil in Houghton et al. 2000). The amount of wood resource and its energy content is estimated with 8% and 20%, of the total amount of biomass per hectare of primary rain forest in these countries for the harvested and burned wood, respectively. The allocation is based on the shares used as wood or burned for the purpose of land clearing.

The land transformation from primary forest to forest, intensive, clear cutting is fully allocated to the provision of stubbed land. Each process which uses the stubbed land has to inventory the square metres as “provision, stubbed land” and in addition a transformation from “forest, intensive, clear cutting” to the type of land occupation relevant for the given process. The land transformation has an important influence on the biodiversity in these areas. This aspect is not modelled directly, but it is possible to assess this impact with impact assessment methods for land transformation. So far these methods have only been developed for Europe, but it would be possible to develop them also for land transformation affecting primary forests in South-America and Asia (e.g. Goedkoop & Spriensma 2000; Köllner 2001).

The time necessary for clear cutting of one hectare was roughly estimated with two weeks.

The use of machinery has been calculated for the amount of harvested wood with European data (Werner et al. 2003). No machinery use is taken into account for the provision of stubbed land.

Air emissions due to the combustion of biomass have been calculated with emission factors derived for primary forests.[20] The factors are provided per kg of dry biomass burned. The emissions are fully allocated to the provision of stubbed land as no good information is available for justifying an allocation choice.[21]

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[20] Personal communication with Angelika Heil, Max Planck Institute for Meteorology, Hamburg, Germany, September 2006. Data are based on (Andreae & Merlet 2001) and further assumptions from Ms. Heil.

[21] Preliminary assumption following a discussion in the ecoinvent Fachgruppe, August 2006.

Tab. 4.5 Unit process raw data for clear cutting of primary forest

	Name	Location	InfrastructureProcess	Unit	clear-cutting, primary forest	round wood, primary forest, clear-cutting, at forest road	provision, stubbed land	clear-cutting, primary forest	StandardDeviation95	GeneralComment	round wood, primary forest, clear-cutting, at forest road	provision, stubbed land
	Location				BR	BR	BR	MY			MY	MY
	InfrastructureProcess				0	0	0	0			0	0
	Unit				ha	m3	m2	ha			m3	m2
allocated products	round wood, primary forest, clear-cutting, at forest road	BR	0	m3	5.21E+1	100	-	0			-	-
	provision, stubbed land	BR	0	m2	1.00E+4	-	100	0			-	-
	round wood, primary forest, clear-cutting, at forest road	MY	0	m3	0	-	-	4.14E+1			100	-
	provision, stubbed land	MY	0	m2	0	-	-	1.00E+4			-	100
resource, biotic	Wood, primary forest, standing	-	-	m3	1.82E+2	29	71	1.45E+2	1.24	(4,3,1,1,1,4); Wood burned or harvested	29	71
	Energy, gross calorific value, in biomass, primary forest	-	-	MJ	1.97E+6	29	71	1.56E+6	1.24	(4,3,1,1,1,4); Wood burned or harvested	29	71
resource, land	Transformation, from tropical rain forest	-	-	m2	1.00E+4	-	100	1.00E+4	2.06	(4,3,1,1,1,4); Calculation	-	100
	Transformation, to forest, intensive, clear-cutting	-	-	m2	1.00E+4	-	100	1.00E+4	2.06	(4,3,1,1,1,4); Calculation	-	100
	Occupation, construction site	-	-	m2a	3.85E+2	29	71	3.85E+2	1.58	(4,3,1,1,1,4); Rough estimation for 2 weeks necessary for clear-cutting	29	71
technosphere	power sawing, without catalytic converter	RER	0	h	1.24E+1	100	-	9.86E+0	1.11	(3,1,1,1,1,1); Rough estimation with European forestry data for harvesting of wood, Werner 2003	100	-
	diesel, burned in building machine	GLO	0	MJ	3.80E+3	100	-	3.02E+3	1.11	(3,1,1,1,1,1); Rough estimation with European forestry data for harvesting of wood, Werner 2003	100	-
emission air, low population density	Carbon dioxide, land transformation	-	-	kg	1.20E+5	-	100	9.54E+4	1.40	(2,1,1,1,1,na); Burning of 20% of the biomass	-	100
	Carbon monoxide, fossil	-	-	kg	7.84E+3	-	100	6.23E+3	5.00	(2,1,1,1,1,na); Burning of 20% of the biomass, literature data	-	100
	Methane, fossil	-	-	kg	5.14E+2	-	100	4.09E+2	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Ethene	-	-	kg	1.47E+2	-	100	1.17E+2	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Ethyne	-	-	kg	3.06E+1	-	100	2.43E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Propene	-	-	kg	1.03E+2	-	100	8.21E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Benzene	-	-	kg	3.06E+1	-	100	2.43E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Toluene	-	-	kg	1.89E+1	-	100	1.50E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Formic acid	-	-	kg	9.15E+1	-	100	7.27E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Acetic acid	-	-	kg	3.27E+2	-	100	2.60E+2	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Formaldehyde	-	-	kg	8.13E+1	-	100	6.46E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Acetaldehyde	-	-	kg	4.98E+1	-	100	3.96E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Methanol	-	-	kg	1.60E+2	-	100	1.27E+2	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Phenol	-	-	kg	4.28E-1	-	100	3.40E-1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Acetone	-	-	kg	5.28E+1	-	100	4.19E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Furan	-	-	kg	2.60E+1	-	100	2.06E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Isoprene	-	-	kg	1.21E+0	-	100	9.58E-1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Ammonia	-	-	kg	9.88E+1	-	100	7.85E+1	1.21	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Cyanide	-	-	kg	2.28E+1	-	100	1.81E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Nitrogen oxides	-	-	kg	1.41E+2	-	100	1.12E+2	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Acetonitrile	-	-	kg	1.37E+1	-	100	1.09E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Particulates, < 2.5 um	-	-	kg	6.88E+2	-	100	5.47E+2	3.00	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Particulates, > 2.5 um, and < 10um	-	-	kg	5.76E+1	-	100	4.57E+1	2.00	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Sulfur dioxide	-	-	kg	4.35E+1	-	100	3.46E+1	1.07	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Dinitrogen monoxide	-	-	kg	1.52E+1	-	100	1.21E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Ethane	-	-	kg	9.13E+1	-	100	7.26E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Propane	-	-	kg	7.92E+1	-	100	6.29E+1	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Terpenes	-	-	kg	1.14E+1	-	100	9.06E+0	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Ethanol	-	-	kg	1.29E+0	-	100	1.03E+0	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
	Xylene	-	-	kg	4.50E+0	-	100	3.58E+0	1.50	(2,1,1,1,1,na); Burning of 20% of the bioma	-	100
informations	C bound bio biomass (kg/ha)				190000			151000				
	Biomass (kg/ha)				380000			302000				
	Wood density (kg/m3)				583			583				
	Wood (m3/ha)				651			518				
	HHV (MJ/kg fm)				18.5			18.5				
	HHV (MJ/kg dm)				21.0			21.0				

4.7 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 4.6 shows selected LCI results and the cumulative energy demand for the clear cutting of primary forest and the provision of wood from these production places. The emissions of carbon dioxide due to land transformation are a relevant aspect for the provision of stubbed land.

Tab. 4.6 Selected LCI results and the cumulative energy demand for the clear cutting of primary forests and the provision of wood from these production places

		Name		provision, stubbed land	provision, stubbed land	round wood, primary forest, clear-cutting, at forest road	round wood, primary forest, clear-cutting, at forest road
		Location		BR	MY	BR	MY
		Unit	Unit	m2	m2	m3	m3
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	-	-	128.4	128.4
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	-	-	3.0	3.0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	-	-	0.5	0.5
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	-	-	0.1	0.1
	cumulative energy demand	renewable energy resources,	MJ-Eq	-	-	2.9	2.9
LCI results							
resource	Land occupation	total	m2a	2.7E-2	2.7E-2	2.6E+0	3.2E+0
air	Carbon dioxide, fossil	total	kg	0	0	7.5E+0	7.5E+0
air	NMVOC	total	kg	1.2E-1	9.4E-2	1.4E-1	1.4E-1
air	Nitrogen oxides	total	kg	1.4E-2	1.1E-2	8.1E-2	8.1E-2
air	Sulphur dioxide	total	kg	4.4E-3	3.5E-3	1.3E-2	1.3E-2
air	Particulates, < 2.5 um	total	kg	6.9E-2	5.5E-2	7.5E-3	7.5E-3
water	BOD	total	kg	0	0	3.7E-2	3.7E-2
soil	Cadmium	total	kg	0	0	1.0E-7	1.0E-7
Further LCI results							
air	Carbon dioxide, biogenic	total	kg	0	0	-1.9E-1	-1.9E-1
air	Carbon dioxide, land transformation	low population density	kg	1.2E+1	9.5E+0	2.6E-5	2.6E-5
air	Methane, biogenic	total	kg	0	0	4.0E-6	4.0E-6
air	Carbon monoxide, biogenic	total	kg	0	0	2.8E-5	2.8E-5

4.8 Conclusions

The life cycle inventory for the clear cutting of primary forest has been elaborated in support of the life cycle inventories of soybean and palm fruit bunches production. Further research is necessary in order to establish a better dataset also valuable for the production of wood and for the provision of stubbed land for other purposes than agriculture.

References

Achard et al. 2002	Achard F., Eva H. D., Stibig H. J., Mayaux P., Gallego J., Richards T. and Malingreau J. P. (2002) Determination of deforestation rates of the world's humid tropical forests. *In: Science*, **2002**(297), pp. 999-1002.
Andreae & Merlet 2001	Andreae M. O. and Merlet P. (2001) Emission of trace gases and aerosols from biomass burning. *In: Global Biogeochem. Cyc.*, **15**(4), pp. 955-966.
Brown 1997	Brown S. (1997) Estimating Biomass and Biomass Change of Tropical Forests: a Primer. Food and Agriculture Organization of the United Nations Rome.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.
Goedkoop & Spriensma 2000	Goedkoop M. and Spriensma R. (2000) The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, The Netherlands, retrieved from: www.pre.nl/eco-indicator99/.
Houghton et al. 2000	Houghton R. A., Skole D. L., Nobre C. A., Hackler J. L., Lawrence K. T. and Chomentowski W. H. (2000) Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *In: Nature*, **403**, pp. 301-304.

Köllner 2001	Köllner T. (2001) Land Use in Product Life Cycles and its Consequences for Ecosystem Quality. Dissertation Nr. 2519. Universität St. Gallen, Hochschule für Wirtschafts-, Rechts- und Sozialwissenschaften (HSG), St. Gallen.
Ministry of Science and Technology 2004	Ministry of Science and Technology (2004) Brazil's initial national communication to the United Nations framework convention on climate change. Ministry of Science and Technology, Brasilia, retrieved from: http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.
Ministry Of Science- Technology And The Environment 2000	Ministry Of Science- Technology And The Environment (2000) Malaysia - Initial National Communication, retrieved from: http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.
Werner et al. 2003	Werner F., Althaus H.-J., Künniger T., Richter K. and Jungbluth N. (2003) Life Cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent 2000 No. 9. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

5 Corn, production in the USA

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Last changes: 2006

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5.1 Introduction

Corn or maize (*Zea mays* L.) is a cereal grain of the family *Poaceae*.

It is widely cultivated throughout the world. Each year more corn is produced than any other grain. The United States produces almost half of the world's harvest. Other top producing countries are China, Brazil, France, Indonesia, and South Africa (FAOSTAT 2006).

The functional unit is 1 kg of corn grains (fresh matter), at farm, USA. The properties of corn grains are given in Tab. 5.1.

Tab. 5.1 Properties of corn grains (Nemecek et al. 2004)

Property	Value	Unit
Water	0.14	kg/kg corn fresh matter
C content	0.375	kg/kg corn fresh matter
HHV	15.9	MJ/kg corn fresh matter
Cd	0.026	mg/kg corn fresh matter
Cr	0.28	mg/kg corn fresh matter
Cu	2.17	mg/kg corn fresh matter
Pb	0.26	mg/kg corn fresh matter
Ni	1.0	mg/kg corn fresh matter
Zn	18.7	mg/kg corn fresh matter

5.2 Yields

NASS (2005) reports data for the production of corn in the USA. In Tab. 5.2 values for the area, the production amounts and the yields are given.

Tab. 5.2 Corn production in the USA in 2005 (NASS 2005)

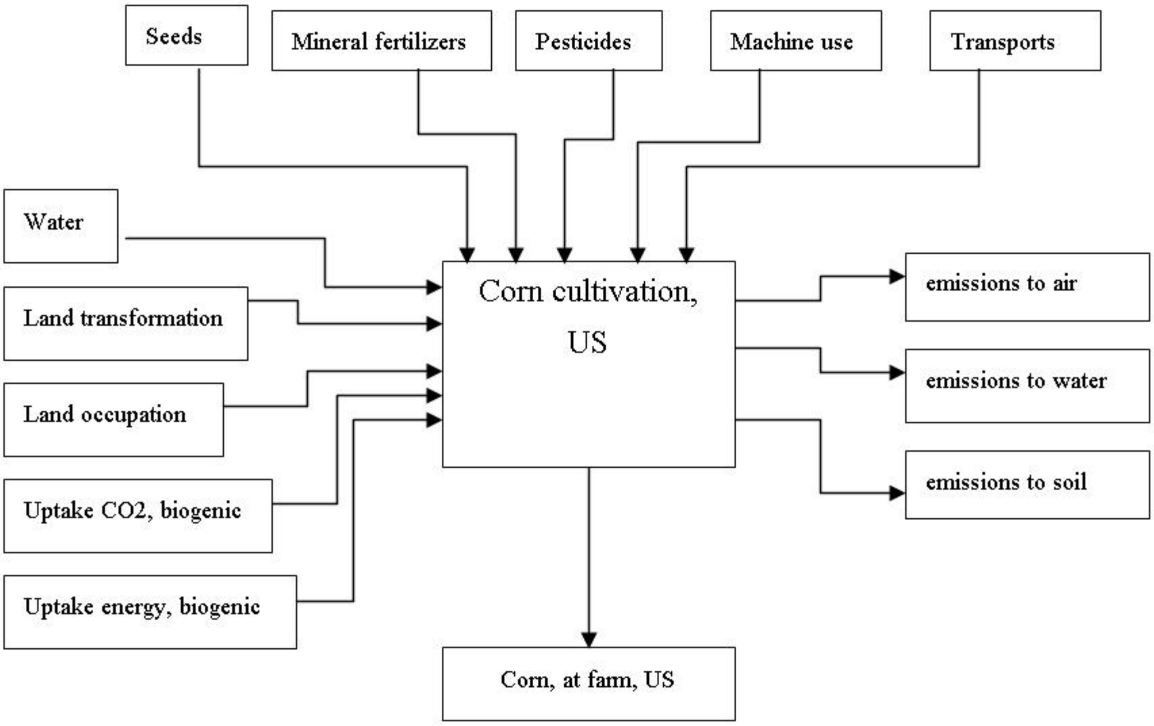
Corn production	USA
Area (ha)	30081497
Grains yield (kg/ha)	9315
Production (t)	2.8E08

5.3 System Characterisation

This report corresponds to the production of **1 kg corn grains, at farm, in the USA**.

All data in the present report refer to 1 kg corn grains fresh matter. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of the raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

Fig. 5.1 Process flow chart for the cultivation of corn in the USA



5.4 Data sources

Most data are taken from NREL (2006), a life cycle inventory of corn production in the USA, that is based on official statistics and represents 91 % of the US corn production.

Some data are taken from IFA (2006), that is based on official statistics, and KTBL (2004), that is based on representative data for the corn production in Germany.

5.5 Raw materials and auxiliaries

5.5.1 Fertilizers

In Tab. 5.3 quantities for the fertilizer use in the USA are given. In this study values for the amounts of used fertilizers are taken from NREL (2006) because of their major representativeness. Data for the products, which are used as fertilizers are taken from IFA (2006).

Tab. 5.3 Fertilizer use in the corn cultivation in the USA (IFA 2006)

Region	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]	Lime [kg/ha/y]
Eastern part of Corn belt (IFA 2006)	170	84	78	na
Western part of Corn belt (IFA 2006)	145	54	56	na
USA (NREL 2006) (used for this study)	157.2	54.5	67	283.3

Tab. 5.4 Fertilizer use by product in the USA (IFA 2006)

Nutrient	Product	%
N	Anhydrous ammonia	50
	Urea	21
	Ammonium nitrate	29
P2O5	DAP	100
K2O	Potassium chloride	100

Tab. 5.5 Use of fertilizers in the cultivation of corn in this study

Product	kg kg^{-1} corn
ammonia, liquide, at plant	8.44E-03
urea as N	3.54E-03
ammonium nitrate as N	4.89E-03
diammonium phosphate as P2O5	5.85E-03
potassium chloride as K2O	7.19E-03
limestone	3.04E-02

5.5.2 Water

The corn fields the USA are irrigated. NREL (2006) reports an amount of 40.86 m^3 water per ha. In this study the irrigation is calculated with the dataset “irrigating". The value is calculated from the water use of the irrigating dataset.

5.5.3 Pesticides and Biological Control

USDA (2004) reports amounts of pesticides use in the corn cultivation in the USA. The data are based on official statistics of the USA. They are given here.

Tab. 5.6 Pesticides use in the corn cultivation (USDA 2004)

Pesticide group	Pesticide	Amount [kg/ha/y]	Used dataset
Herbicides	2,4-D	0.02298	2,4-D
	Acetamide	0.00942	acetamide-anilide-compounds
	Acetic acid	0.00538	Pesticides, unspecific
	Acetochlor	0.5537	Pesticides, unspecific
	Alachlor	0.03856	Alachlor
	Atrazine	0.86126	Atrazine
	Bromoxynil	0.00605	nitrile-compounds
	Dicamba	0.01614	Dicamba
	Diflufenzopyr-sodium	0.00179	diphenylether-compounds
	Dimethenamid	0.01883	acetamide-anilide-compounds
	Dimethenamid-P	0.02802	acetamide-anilide-compounds
	Flumetsulam	0.00314	Pesticides, unspecific
	Foramsulfuron	0.00034	sulfonyl-urea-compounds
	Glufosinate-ammonium	0.0111	organophosphorus-compounds
	Glyphosate	0.18315	Glyphosate
	Imazapyr	4.4834E-05	phenoxy-compounds
	Imazethapyr	1.56919E-04	phenoxy-compounds
	Isoxaflutole	0.00538	cyclic-N-compounds
	Mesotrione	0.01457	Pesticides, unspecific
	Metolachlor	0.10558	Metolachlor
	Nicosulfuron	0.00247	sulfonyl-urea-compounds
	Paraquat	0.00572	bipyridylium-compounds
	Pendimethalin	0.02309	dinitroaniline-compounds
	Primisulfuron	0.00112	sulfonyl-urea-compounds
	Prosulfuron	0.0002	sulfonyl-urea-compounds
	Rimsulfuron	0.00112	sulfonyl-urea-compounds
	S-Metolachlor	0.29389	Metolachlor
	Simazine	0.02264	triazine-compounds
Insecticides	Bifenthrin	0.00202	pyretroid-compounds
	Chlorpyrifos	0.04483	organophosphorus-compounds
	Cyfluthrin	4.7076E-04	pyretroid-compounds
	Fipronil	0.00269	nitrile-compounds
	lambda-Cyhalothrin	0.000224	pyretroid-compounds
	Permethrin	0.001009	pyretroid-compounds
	Tebupirimphos	0.009415	organophosphorus-compounds
	Tefluthrin	0.007398	pyretroid-compounds
	Terbufos	0.025107	organophosphorus-compounds
	Zeta-cypermethrin	0.000336	pyretroid-compounds
Total Pesticides		2.329	

Tab. 5.7 Use of pesticides in the cultivation of corn in this study

Product	kg kg^{-1} corn
2,4-D	2.47E-06
acetamide-anilide-compounds	6.04E-06
alachlor	4.14E-06
atrazine	9.25E-05
nitrile-compounds	9.34E-07
dicamba	1.73E-06
diphenylether-compounds	1.93E-07
sulfonyl-urea-compounds	5.63E-07
organophosphorus-compounds	9.71E-06
glyphosate	1.97E-05
phenoxy-compounds	2.17E-08
cyclic-N-compounds	5.78E-07
metolachlor	4.29E-05
bipyridylium-compounds	6.14E-07
dinitroaniline-compounds	2.48E-06
triazine-compounds	2.43E-06
pyretroid-compounds	1.23E-06
pesticides, unspecific	6.19E-05
total pesticides	2.5E-04

5.5.4 Seed

About 200 kg seeds per ha are used (KTBL 2004). The use of the seeds is calculated with the dataset “maize seed IP, at regional storehouse, CH” from Nemecek et al. (2004).

5.6 Energy and machine usage

Cultivation

NREL (2006) reports data for the diesel use in the cultivation of corn in the USA. The data are based on statistics and are representative for 91% of the area that is cultivated with corn in the USA. The usage of machines is extrapolated from the proportions of several field works in the corn cultivation in Germany (KTBL 2004), see Tab. 5.9. These proportions of the diesel consumptions are taken to calculate the machine usage base on the diesel consumptions of the several field works, which are given in Nemecek et al. (2004).

Tab. 5.8 Diesel consumption in the corn cultivation

Process	NREL 2006
Diesel consumption [l/ha/y]	66.75

Tab. 5.9 Machine use in the corn cultivation

Process	% of the total diesel consumption in the German corn cultivation, according to KTBL (2004)	**Machine use** [ha/kg corn]
fertilizing	4.1	5.49E-05
ploughing	31.3	8.60E-05
harrowing	15.4	2.49E-04
currying	4.5	2.00E-04
sowing	2.0	3.80E-05
application plant protection	4.5	8.25E-05
combine harvesting	27.3	9.59E-06
chiseling	10.9	1.26E-04

5.7 Transportation

For the transports of the inputs to the farm the values, which are given by NREL (2006), are used. The transports of the inputs to the field and of the harvested corn from the field to the farm are calculated with the standard distances, which are given in Nemecek et al. (2004).

Tab. 5.10 Transports in the corn cultivation in the USA

Material	**Tractor [km]**	**Rail [tkm]**	**Lorry 32 t [kg diesel]**
Total inputs		4.63E-02	1.014E-03
corn	15		
fertilizers	15		
seeds	15		
pesticides	15		

The transports with lorry are converted with the diesel consumption of lorry transports from Spielmann et al. (2004).

Tab. 5.11 Transport service requirements per kg corn

Material	**Value**
lorry 32t [tkm]	2.86E-03
rail [tkm]	4.39E-03
tractor and trailer [tkm]	1.58E-02

5.8 Drying

The drying of the corn is calculated with the dataset “grain drying, high temperature” according to Nemecek et al. (2004). The corn is dried from 39 % moisture at harvest to 14 % moisture at storage. These values are based on Swiss data (Nemecek et al. 2004) because no data are available for moisture of corn in the USA.

5.9 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account) and the yield per area unit. The land occupied was always considered as “Occupation, arable”.

Land transformation was calculated on the basis of the area required to produce 1 kg of corn. The type of use before establishment of the crop was assumed to be arable land.

In Tab. 5.12 the accounted amounts of land use are given. They are calculated with a yield of 9315 t corn per year and ha. The occupation is calculated during 7 months per year (Nemecek et al. 2004).

Tab. 5.12 Amounts of land use for the cultivation of corn

Land use	per kg corn
Transformation from arable [m^2]	1.097
Transformation to arable [m^2]	1.097
Occupation, arable, irrigated [m^2a]	0.640

5.10 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon balance. The carbon content of the seeds is calculated as carbon input. The biomass energy is calculated from the energy content of the corn.

Tab. 5.13 Uptake of CO_2 and biomass energy

	per kg corn fresh matter
CO_2, biogenic [kg]	1.35
Energy, biomass [MJ]	18.5

5.11 Emissions to air

NREL (2006) reports values for the emissions of NH_3, N_2O, and NO_x to air from the mineral fertilizers. These data are representative for 91 % of the US corn cultivation

In Tab. 5.14 values for the emissions to air from corn cultivation are given.

Tab. 5.14 Emissions to air from corn cultivation

Emissions to air	Emission factor (% of the N contained in the fertilizer)	Emission (kg/kg corn)
NH3-N	6.5	1.1E-03
N2O	3.1	5.26E-04
NOx	1.8	2.98E-04

5.12 Emissions to water

For the phosphorus emissions to water the emission factors are calculated according to method, which is described for Switzerland in Nemecek et al. (2004).

Randall et al. (2003) report a nitrogen loss of about 32 % of the N contained in the fertilizers. The N is leached as nitrate. The data are based on field measurements from 1987 to 1994.

Tab. 5.15 Emissions to water from corn cultivation

Emission	Emission factor (% of the nutrient contained in the fertilizer)	Value (kg/kg corn)
Phosphorus, to surface water	1.67	9.75E-05
Phosphorus, to ground water	0.13	7.510E-05
Nitrate, to ground water	32	2.39E-02

5.13 Emissions to soil

The applied pesticides are calculated as emissions to soil.

The differences between the inputs of heavy metals contained in the fertilizers and the seeds and the outputs through harvested products are assumed to be heavy metal emissions to soil. Some heavy metals are calculated as heavy metal uptake because the outputs are higher than the inputs.

Tab. 5.16 Emissions to soil from corn cultivation

Emission	Value (kg/kg corn)
Cd	-1.88E-08
Cr	4.45E-08
Cu	-1.50e-06
Ni	-3.28E-07
Pb	2.64E-07
Zn	-5.90E-06
2,4-D	3.04E-06
Acetamide	1.01E-06
Acetochlor	5.94E-05
Alachlor	4.14E-06
Atrazine	9.25E-05
Bromoxynil	6.50E-07
Dicamba	1.73E-06
Diflufenzopyr-sodium	1.93E-07
Dimethenamid	5.03E-06
Flumetsulam	3.37E-07
Foramsulfuron	3.61E-08
Glufosinate	1.19E-06
Glyphosate	1.97E-05
Imazapyr	4.81E-09
Imazethapyr	1.68E-08
Isoxaflutole	5.78E-07
Mesotrione	1.56E-06
Metolachlor	4.29E-05
Nicosulfuron	2.65E-07
Paraquat	6.14E-07
Pendimethalin	2.48E-06
Primisulfuron	1.20E-07
Prosulfuron	2.17E-08
Rimsulfuron	1.20E-07
Simazine	2.43E-06
Bifenthrin	2.17E-07
Chlorpyrifos	4.81E-06
Cyfluthrin	5.05E-08
Fipronil	2.89E-07
Lamda-Cyhalothrin	2.41E-08
Permethrin	1.08E-07
Tebupirimphos	1.01E-06
Tefluthrin	7.94E-07
Terbufos	2.70E-06
Cypermethrin	3.61E-08

1.1 Life cycle inventory of corn cultivation and data quality considerations

Tab. 5.17 shows the life cycle inventory and the data quality indicators for the cultivation of corn. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 5.17 Unit process raw data for the cultivation of corn

401	InputGroup	OutputGroup	Name	Location	InfrastructureProcess	Unit	corn, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location				US			
493			InfrastructureProcess				0			
403			Unit				kg			
	-	0	corn, at farm	US	0	kg	1.00E+0			
resource, in air	4	-	Carbon dioxide, in air	-	-	kg	1.35E+0	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	-	MJ	1.59E+1	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
technosphere	5	-	maize seed IP, at regional storehouse	CH	0	kg	2.15E-2	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	ammonia, liquid, at regional storehouse	RER	0	kg	8.44E-3	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	urea, as N, at regional storehouse	RER	0	kg	3.54E-3	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	ammonium nitrate, as N, at regional storehouse	RER	0	kg	4.89E-3	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	5.85E-3	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	potassium chloride, as K2O, at regional storehouse	RER	0	kg	7.19E-3	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	lime, from carbonation, at regional storehouse	CH	0	kg	3.04E-2	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	irrigating	CH	0	ha	3.66E-6	1	1.05	(1,2,1,1,1,1); NREL 2006
	5	-	2,4-D, at regional storehouse	RER	0	kg	2.47E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	acetamide-anillide-compounds, at regional storehouse	RER	0	kg	6.04E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	alachlor, at regional storehouse	RER	0	kg	4.14E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	atrazine, at regional storehouse	RER	0	kg	9.25E-5	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	nitrile-compounds, at regional storehouse	RER	0	kg	9.39E-7	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	dicamba, at regional storehouse	RER	0	kg	1.73E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	diphenylether-compounds, at regional storehouse	RER	0	kg	1.93E-7	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	[sulfonyl]urea-compounds, at regional storehouse	RER	0	kg	5.63E-7	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	organophosphorus-compounds, at regional storehouse	RER	0	kg	9.71E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	glyphosate, at regional storehouse	RER	0	kg	1.97E-5	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	phenoxy-compounds, at regional storehouse	RER	0	kg	2.17E-8	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	cyclic N-compounds, at regional storehouse	RER	0	kg	5.78E-7	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	metolachlor, at regional storehouse	RER	0	kg	4.29E-5	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	bipyridylium-compounds, at regional storehouse	RER	0	kg	6.14E-7	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	dinitroaniline-compounds, at regional storehouse	RER	0	kg	2.48E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	triazine-compounds, at regional storehouse	RER	0	kg	2.43E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	pyretroid-compounds, at regional storehouse	CH	0	kg	1.23E-6	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	pesticide unspecified, at regional storehouse	RER	0	kg	6.28E-5	1	1.05	(1,2,1,1,1,1); NASS 2004
	5	-	fertilising, by broadcaster	CH	0	ha	5.49E-5	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	tillage, ploughing	CH	0	ha	8.60E-5	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	tillage, harrowing, by spring tine harrow	CH	0	ha	2.49E-4	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	tillage, currying, by weeder	CH	0	ha	2.00E-4	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	sowing	CH	0	ha	3.80E-5	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	application of plant protection products, by field sprayer	CH	0	ha	8.25E-5	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	combine harvesting	CH	0	ha	9.59E-6	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	tillage, cultivating, chiselling	CH	0	ha	1.26E-4	1	1.21	(1,2,1,1,3,1); NREL 2006, KTBL 2004
	5	-	maize drying	CH	0	kg	4.10E-1	1	1.12	(1,1,3,3,1,1); Nemecek 2004
	5	-	transport, tractor and trailer	CH	0	tkm	2.86E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, lorry 32t	RER	0	tkm	4.39E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, freight, rail	RER	0	tkm	1.58E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
resources	4	-	Transformation, from arable	-	-	m2	1.07E+0	1	2.00	(1,1,1,1,1,1); NASS 2005
	4	-	Transformation, to arable	-	-	m2	1.07E+0	1	2.00	(1,1,1,1,1,1); NASS 2005
	4	-	Occupation, arable	-	-	m2a	6.26E-1	1	1.50	(1,1,1,1,1,1); NASS 2005
emission air, low population density	-	4	Ammonia	-	-	kg	1.10E-3	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	-	kg	5.26E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	-	kg	2.98E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, river	-	4	Phosphorus	-	-	kg	9.75E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	-	kg	7.51E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrate	-	-	kg	2.39E-2	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission agricultural soil	-	4	Cadmium	-	-	kg	-1.88E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Chromium	-	-	kg	4.45E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Copper	-	-	kg	-1.50E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Nickel	-	-	kg	-3.29E-7	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Lead	-	-	kg	2.64E-7	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Zinc	-	-	kg	-5.90E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	2,4-D	-	-	kg	3.04E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Acetamide	-	-	kg	1.01E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Acetochlor	-	-	kg	5.94E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Alachlor	-	-	kg	4.14E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Atrazine	-	-	kg	9.25E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Bromoxynil	-	-	kg	6.50E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Dicamba	-	-	kg	1.73E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Diflufenzopyr-sodium	-	-	kg	1.93E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Dimethenamid	-	-	kg	5.03E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Flumetsulam	-	-	kg	3.37E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Foramsulfuron	-	-	kg	3.61E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Glufosinate	-	-	kg	1.19E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Glyphosate	-	-	kg	1.97E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Imazapyr	-	-	kg	4.81E-9	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Imazethapyr	-	-	kg	1.68E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Isoxaflutole	-	-	kg	5.78E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Mesotrione	-	-	kg	1.56E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Metolachlor	-	-	kg	4.29E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Nicosulfuron	-	-	kg	2.65E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Paraquat	-	-	kg	6.14E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Pendimethalin	-	-	kg	2.48E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Primisulfuron	-	-	kg	1.20E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Prosulfuron	-	-	kg	2.17E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Rimsulfuron	-	-	kg	1.20E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Simazine	-	-	kg	2.43E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Bifenthrin	-	-	kg	2.17E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Chlorpyrifos	-	-	kg	4.81E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Cyfluthrin	-	-	kg	5.05E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Fipronil	-	-	kg	2.89E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Lamda-Cyhalothrin	-	-	kg	2.41E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Permethrin	-	-	kg	1.08E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Tebupirimphos	-	-	kg	1.01E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Tefluthrin	-	-	kg	7.94E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Terbufos	-	-	kg	2.70E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Cypermethrin	-	-	kg	3.61E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application

5.14 Cumulative Results and Interpretation

5.14.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

5.14.2 Cultivation of corn

Tab. 5.18 shows selected LCI results and the cumulative energy demand for the cultivation of corn and a comparison of these results with the ecoinvent dataset grain maize, IP, at farm, CH. Most differences between these datasets are due to the different machine usage and the different fertilizer use in Switzerland and the USA. The difference in the N_2O emission are caused by the different fertilizer use and the different calculation model for this emission.

Land occupation differs because of the cultivation of intercrops in corn fields in Switzerland. This is not usual in the USA.

Tab. 5.18 Selected LCI results and the cumulative energy demand for the cultivation of corn

c		Name		corn, at farm	grain maize IP, at farm
		Location		US	CH
		Unit	Unit	kg	kg
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.5	5.2
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.4	3.0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.9
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	16.3	16.0
LCI results					
resource	Land occupation	total	m2a	7.5E-1	1.6E+0
air	Carbon dioxide, fossil	total	kg	2.2E-1	3.4E-1
air	NMVOC	total	kg	1.7E-4	2.8E-4
air	Nitrogen oxides	total	kg	1.0E-3	1.4E-3
air	Sulphur dioxide	total	kg	5.5E-4	6.4E-4
air	Particulates, < 2.5 um	total	kg	7.9E-5	1.2E-4
air	Dinitrogen monoxide	total	kg	7.0E-4	1.1E-3
air	Methane, fossil	total	kg	2.9E-4	4.7E-4
water	BOD	total	kg	6.2E-4	9.4E-4
soil	Cadmium	total	kg	3.5E-8	3.1E-7
water	Phosphorus	total	kg	7.5E-6	1.0E-8
water	Nitrate	total	kg	2.7E-2	4.2E-2
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	-1.4E+0	-1.4E+0
air	Carbon dioxide, land transformation	low population density	kg	1.6E-5	8.1E-6
air	Methane, biogenic	total	kg	7.8E-7	2.2E-6
air	Carbon monoxide, biogenic	total	kg	6.0E-6	1.8E-5

Tab. 5.19 shows values for CED, non-renewable, fossil for the two datasets and one value, which was found in literature. The differences are due to the different machine usage and the different fertilizer use.

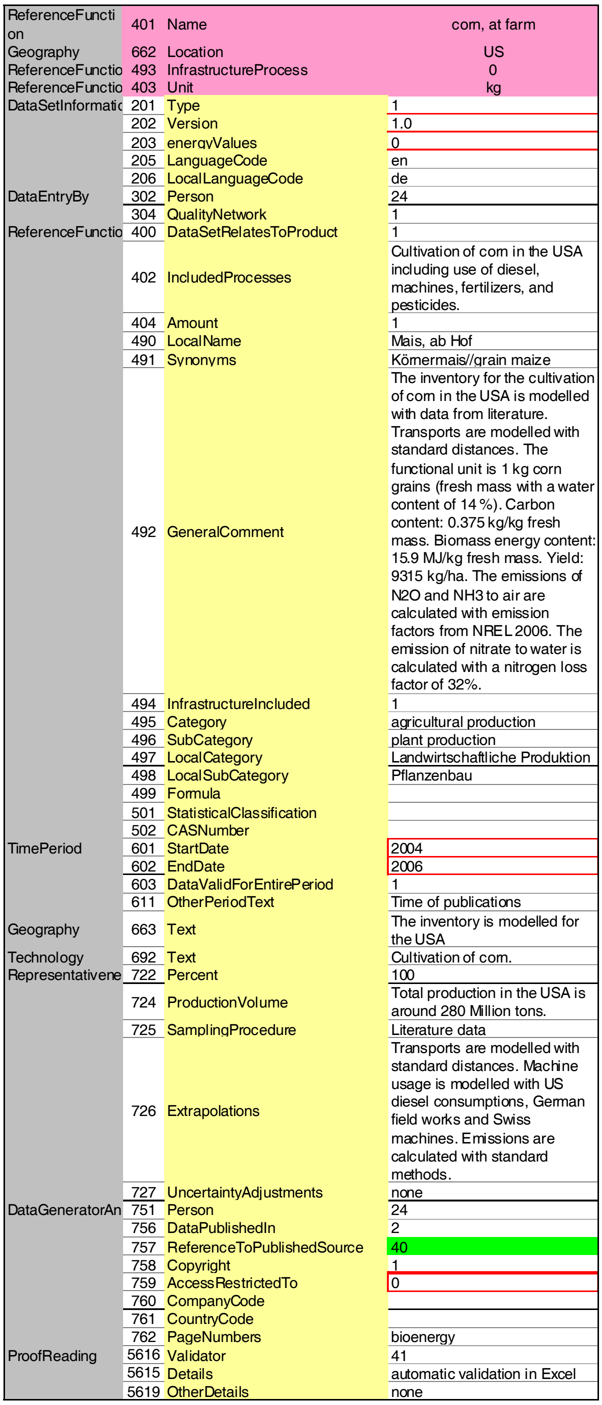
Tab. 5.19 Comparison of CED, CO2 emissions

Emission	**Corn, at farm, US**	**Grain maize, IP, at farm, CH**	**Shapouri et al. 1995 (Corn cultivation in the USA)**
CED, non-renewable energy resources, fossil (MJ-Eq)	3.5	5.2	2.3

5.15 Conclusions

The life cycle inventory for the corn cultivation in the USA is determined largely by the use of fertilizers. For further work the emissions of N2O, NOx and NH3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information



ReferenceFunction	401	Name	corn, at farm
Geography	662	Location	US
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of corn in the USA including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1
	490	LocalName	Mais, ab Hof
	491	Synonyms	Körnermais//grain maize
	492	GeneralComment	The inventory for the cultivation of corn in the USA is modelled with data from literature. Transports are modelled with standard distances. The functional unit is 1 kg corn grains (fresh mass with a water content of 14 %). Carbon content: 0.375 kg/kg fresh mass. Biomass energy content: 15.9 MJ/kg fresh mass. Yield: 9315 kg/ha. The emissions of N2O and NH3 to air are calculated with emission factors from NREL 2006. The emission of nitrate to water is calculated with a nitrogen loss factor of 32%.
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2004
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications
Geography	663	Text	The inventory is modelled for the USA
Technology	692	Text	Cultivation of corn.
Representativene	722	Percent	100
	724	ProductionVolume	Total production in the USA is around 280 Million tons.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances. Machine usage is modelled with US diesel consumptions, German field works and Swiss machines. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	bioenergy
ProofReading	5616	Validator	41
	5615	Details	automatic validation in Excel
	5619	OtherDetails	none

References

FAOSTAT 2006	Faostat Database Query: Corn Production. Retrieved 16. May 2006, from http://faostat.fao.org/faostat/
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.

IFA 2006	IFA (2006): World Fertilizer Use Manual. Retrieved 16. May 2006, from http://www.fertilizer.org/ifa
KTBL 2004	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.: Betriebsplanung Landwirtschaft 2004/2005 – Daten für die Betriebsplanung in der Landwirtschaft. 20. Auflage. Darmstadt
NASS 2005	National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture. Crop Production. Released November 10, 2005
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
NREL 2006	National Rewnewable Energy Laboratory (2006): U.S. Life-Cycle Inventory Database. Retrieved 30. June 2006, from http://hpb-1a.nrel.gov/lci
Randall et al. 2003	Randall, G. W., Vetsch, J. A., Huffman, J. R.: Surface Water Quality. Nitrate Losses in Subsurface Drainage from a Corn–Soybean Rotation as Affected by Time of Nitrogen Application and Use of Nitrapyrin. J. Environ. Qual. 32:1764–1772 (2003)
Shapouri et al. 1995	Shapouri, H, Duffield, J., Graboski, M: Estimating the Net Energy Balance of Corn Ethanol. U.S. Department of Agriculture, Economic Research Service, Office of Energy and New Uses 1995. Agricultural Economic Report No. 721.
Spielmann et al. 2004	Spielmann M., Kägi T., Stadler P. and Tietje O. (2004) Life Cycle Inventories of Transport Services. Final report ecoinvent 2000 No. 14. UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
USDA 2004	United States Department of Agriculture. National Agricultural Statistics Service: Agricultural Chemical Usage 2003. Field Crops Summary. May 2004

6 Oil Palm, production in Malaysia

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Last changes: 2006

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6.1 Introduction

The African Oil Palm (*Elaeis guineensis* Jacq.) is a tropical tree of the family *Arecaceae*. It usually grows in warm climates at altitudes of less than 1600 feet above sea level. The African Oil Palm originates from the Gulf of Guinea in West Africa. Another species, *Elaeis oleifera* (H.B.K) Cortes, comes from Central and South America.

The Oil palm was introduced to Sumatra and Malaysia area in the early 1900s. In 2005 the Malaysian production of Oil Palm fruit was about 75.65 Million tons, which was 43.6 % of the world production (FAOSTAT 2006).

The Oil Palm is monoecious and produces thousands of fruits in compact bunches whose weight varies between 10 and 40 kilograms. The fruit has a single seed, the palm kernel, protected by a wooden endocarp or shell and surrounded by a fleshy mesocarp or pulp. This fruit produces two types of oil: one extracted from the pulp (palm oil) and the other from the kernel (palm kernel oil).

The functional unit is 1 kg of palm fruit bunches (FFB, fresh matter), at farm, MY. The properties of the fruit bunches are given in Tab. 6.1.

Tab. 6.1 Properties of palm fruit bunches (Corley 2003)

Property	Value	Unit
Palm fruits	0.78	kg/kg FFB
Empty fruit bunches	0.22	kg/kg FFB
Water	0.47	kg/kg FFB
Cu	4.69	mg/kg FFB
Zn	4.85	mg/kg FFB
Carbon content	0.313	kg/kg FFB
HHV	16	MJ/kg FFB

6.2 Farming Systems

The Oil Palms are planted as 3-year-old seedlings. The Oil Palm plantations can be used for 25 years (Corley 2003). When the palms are too old for efficient harvesting the fields are replanted. The old palms are felled and shredded by machines. The biomass is then decomposed on the fields.

6.3 Yields

FAOSTAT 2006 reports data for the cultivation of Oil Palm in Malaysia in 2005. In Tab. 6.2 values for the area, the production amounts and the yields are given. The yield, which is used in this study, is based on an average of the last five years to adjust for annual deviations.

Tab. 6.2 Oil palm cultivation in Malaysia (FAOSTAT 2006)

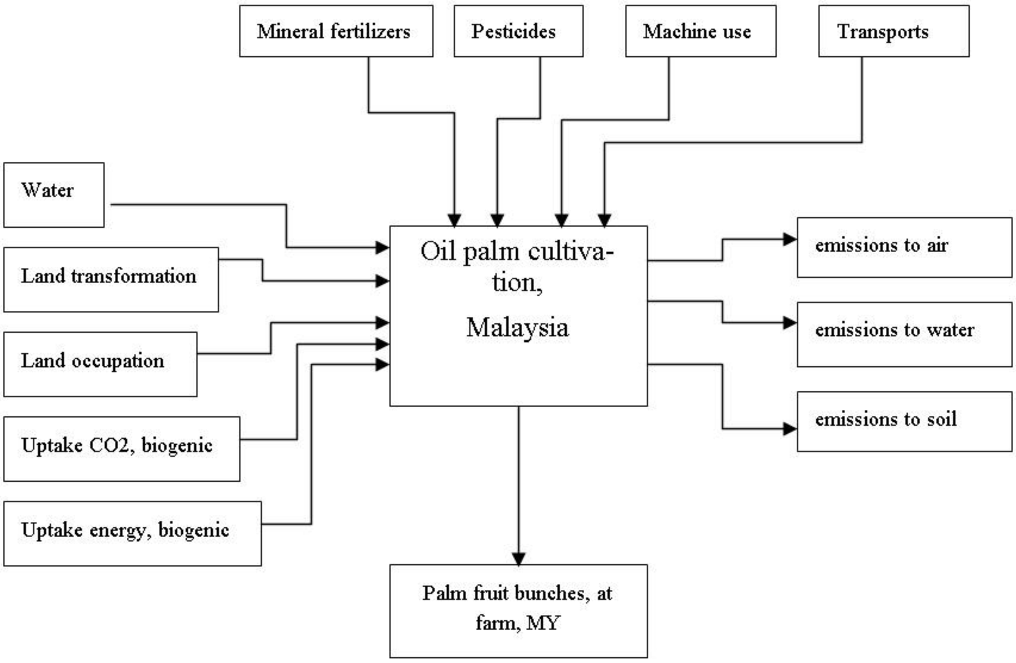
Oil palm cultivation	Malaysia
Harvested area in 2005 (ha)	34100000
Yield in 2001 (kg Oil palm fruits/ha)	17897
Yield in 2002 (kg Oil palm fruits/ha)	17643
Yield in 2003 (kg Oil palm fruits/ha)	20483
Yield in 2004 (kg Oil palm fruits/ha)	20493
Yield in 2005 (kg Oil palm fruits/ha)	20898
Average yield (kg Oil palm fruits/ha)	19483
Average yield (kg FFB/ha)	24978

6.4 System Characterisation

This report corresponds to the dataset for the production of **1 kg palm fruit bunches, at farm, in Malaysia**.

All data in the present report refer to 1 kg FFB fresh matter. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

Fig. 6.1 Process flow chart for the cultivation of oil palms in Malaysia



6.5 Raw materials and auxiliaries

6.5.1 Fertilizers

In Tab. 6.3 quantities for the fertilizer use in Malaysia are given. The data from IFA are based on expert estimations. In this study an average fertilizer use is used.

Corley (2003) reports an amount of 43 kg lime per ha and year for the neutralization of the pH value in the soils in Malaysia. This value is used in this study.

Tab. 6.3 Fertilizer use in Oil Palm cultivation in Malaysia (IFA 2006)

Source	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]	MgO [kg/ha/y]	CaO [kg/ha/y]
IFA 2006	212.3	68.9	353.3	108.9	
Corley 2003	217	27	242	53	43
Ng et al. 1999	100	20	200		
Hofstetter 2006	100	12	150		
Average (this study)	157.3	32	236.3	81	43

Tab. 6.4 Fertilizer use by product in Malaysian Oil Palm cultivation (IFA 2006)

Nutrient	Product
N	Ammonium sulphate
P2O5	MAP/DAP
K2O	Potassium chloride
MgO	Dolomite

Tab. 6.5 Use of fertilizers in Oil Palm cultivation in this study

Product	kg kg^{-1} FFB
ammonium sulphate as N	8.32E-03
diammonium phosphate as P2O5	1.83E-03
potassium chloride as K2O	1.15E-02
dolomite	3.10E-03
limestone	1.72E-03

6.5.2 Water

The Oil Palm plantations in Malaysia are irrigated. Corley (2003) reports an amount of 2100 m^3 water per ha. In this study the irrigation is calculated with the dataset “irrigating" (Nemecek et al. 2004). The value is calculated from the water use of the irrigating dataset.

6.5.3 Pesticides and Biological Control

Tenaganita (2002) reports amounts of pesticides used in Oil Palm cultivation in Malaysia. They are given in Tab. 6.6.

Tab. 6.6 Pesticides use in the Oil Palm cultivation (Tenaganita 2002)

Pesticide group	Pesticide	Amount [kg/ha/y]	Used dataset
Herbicides	2,4-D	1.4588E-01	2,4-D
	Glyphosate	1.0109	Glyphosate
Rodenticides	Warfarin	1.0211E-03	Pesticides, unspecific
	Bromadioline	1.8235E-04	Pesticides, unspecific
Insecticides	Carbufuran	5.0985E-01	(thio)carbamate-compounds
	Cypermethrin	7.1991E-02	pyretroid-compounds
Fungicides	Thiram	1.6499E-03	Pesticides, unspecific
	Benomyl	9.2998E-04	benzomidazole-compounds

Tab. 6.7 Use of pesticides in the cultivation of Oil Palms in this study

Product	kg kg^{-1} FFB
2,4-D	5.84E-06
Glyphosate	4.05E-05
(thio)carbamate-compounds	2.04E-05
pyretroid-compounds	2.88E-06
benzimidazole-compounds	3.72E-08
Pesticides, unspecific	1.14E-07
Total pesticides	6.98E-05

6.5.4 Seedlings

The Oil Palms are planted as seedlings. They are normally produced in huge professional seed-breeding farms (Corley 2003). As the calculation for all inputs and outputs in the production of FFB are based on the whole life time of Oil Palms the only additional input is the transport of seedlings from the seed-breeding farm to the plantation.

6.6 Energy and machine usage

Corley (2003) reports data for the processing of Oil Palm cultivation. As most of the processing is done by hand, the consumption of diesel is relevant only for the application of pesticides, fertilizing, felling and shredding of the palms, and for transports. The values, which are used for the processes, are extrapolated from the diesel use of the datasets (Nemecek et al. 2004). For the shredding the dataset "wood chopping, mobile chopper, in forest" is used (Werner et a. 2003). The biomass shredded comes to around 67.8 tons per ha (Corley 2003).

Tab. 6.8 Machine use in the Oil Palm cultivation

Process	Machine use
fertilizing [ha/kg FFB]	3.36E-05
application plant protection [ha/kg FFB]	3.36E-05
wood chopping [kg/kg FFB]	1.09

6.7 Transportation

For the transport of the FFB to the farm and the transport of the seedlings (36 t per ha per 25 year) to the field, an average distance of 25 km is assumed (Corley 2003). For the transports of fertilizers and pesticides the standard distances, which are given in Frischknecht et al. (2003), are used. Pesticides and fertilizers are converted into the product weight in order to calculate the requirements for transports in tkm. For pesticides a mean active-ingredient content of 50 % is used according to Nemecek et al. (2004). For fertilizers the average nutrient contents are used, which are given in Nemecek et al. (2004).

Tab. 6.9 Transports distances in the Oil Palm cultivation

Material	Tractor and trailer [km]	Lorry 32t [km]	Rail [km]	Remarks
Seedlings	25	-	-	Corley 2003
Fertilizers	15	100	600	Frischknecht et al. 2003
Pesticides	15	100	600	Frischknecht et al. 2003
Limestone	15	100	600	Frischknecht et al. 2003
FFB	25	-	-	Corley 2003

Tab. 6.10 Total transport services for the Oil Palm cultivation

Transport	[tkm per kg FFB]
lorry 32 t	1.35E-03
rail	8.12E-03
tractor	2.64E-02

6.8 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account) and the yield per area unit. The land occupied was always considered as “Occupation, forest, intensive, short cycle”.

Land transformation was calculated on the basis of the area required to produce 1 kg of FFB.

The increase of the area cultivated with Oil Palms is the main reason for the devastation of the tropical rainforests in Malaysia (CSPI 2005). The area, which is used for Oil Palm cultivation, has increased by 150'000 ha per year over the last 10 years (USDA 2004). Because of the very high increase of the cultivated area in the last 20 years, it is assumed that 100 % of the area is transformed from tropical rainforest. The transformation from tropical rainforest is calculated as “provision, stubbed land, MY”.

In Tab. 6.11 the accounted amounts of land use are given. They are calculated with a yield of 24.978 t FFB per ha per year. The occupation is calculated as permanent for 28 years (Corley 2003).

Tab. 6.11 Amounts of land use for the cultivation of Oil Palms in Malaysia

Land use	per kg FFB
Provision stubbed land MY [m2]	1.6E-02
Transformation to forest, intensive, short cycle [m2]	1.6E-02
Occupation, forest, intensive, short cycle [m2a]	4.48E-01

6.9 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon content of FFB. The biomass energy is calculated from the energy content of the FFB.

Tab. 6.12 Uptake of CO_2 and biomass energy

	per kg FFB fresh matter
CO_2, biogenic [kg]	1.148
Energy, biomass [MJ]	16

6.10 Carbon loss from soil after deforestation

From the soil 16.1 tons of carbon per ha are lost due to conversion from rainforest to agricultural area in Asia (Fearnside 2000). The lost carbon from soil is calculated as consumption of the resource "carbon, in organic matter, in soil". This leads to an emission of 59 tons of CO2 per ha deforestated rainforest. All CO2 emissions from the deforestation are allocated to the use as agricultural land.

Tab. 6.13 Consumption of carbon in soil

Resource	per ha rainforest	per kg FFB
Carbon, in organic matter, in soil (kg)	16100	2.58E-02

6.11 Emissions to air

For the emission of NH_3, N_2O, and NO_x to air from the mineral fertilizers the emission factors according to Nemecek et al. (2004) are used:

The NH_3-N emissions are calculated with an emissions factor of 8 % for ammonium sulphate.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that is leached as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

The emission of CO2 caused by the carbon loss from soil after deforestation of the tropical rainforest in Malaysia is calculated as “CO2, land transformation”.

In Tab. 6.14 values for emissions to air from Oil Palm cultivation are given.

Tab. 6.14 Emissions to air from Oil Palm cultivation

Emission	Value	Unit	Source
NH3-N	5.04E-04	[kg/kg FFB]	calculated from the N-input
N2O	2.18E-04	[kg/kg FFB]	calculated from the N-input and nitrate leaching
NOx	4.58E-05	[kg/kg FFB]	calculated from the N-input
CO2, land transformation	9.45E-02	[kg/kg FFB]	from deforestation

6.12 Emissions to water

For the phosphorus emissions to water the emission factors are calculated according to the method, which is described for Switzerland in Nemecek et al. (2004). As no information is available about nitrate leaching from Oil Palm plantation in Malaysia a rough estimation is done: the nitrate to groundwater emissions are calculated with an emission factor of 20 % of the N contained in the fertilizer. In arable crops the nitrate leaching is around 30 % of the N-input (Ostermayer 2002), in permanent short cycle forests it is assumed to be lower.

Tab. 6.15 Emissions to water from Oil Palm cultivation

Emission	Value
Phosphorus, to surface water (kg/kg FFB)	7.79E-06
Phosphorus, to ground water (kg/kg FFB)	2.80E-06
Nitrate, to ground water (kg/kg FFB)	5.58E-03

6.13 Emissions to soil

The applied pesticides are calculated as emissions to soil.

The mineral fertilizers contain heavy metals. As no information is available about the heavy metal content of Oil Palms except for Cu and Zn, a rough estimation is done: 50 % of the other heavy metal inputs are calculated as emissions to soil. Cu and Zn are calculated as heavy metal uptake because the outputs are higher than the inputs.

Tab. 6.16 Emissions to soil from Oil Palm cultivation

Emission	Value (kg/kg FFB)
Cd	1.44E-09
Cr	5.84E-08
Cu	-3.83E-06
Ni	7.69E-08
Pb	7.48E-08
Zn	-4.22E-06
2,4-D	5.84E-06
Glyphosate	4.05E-05
Carbufuran	2.04E-05
Cypermethrin	2.88E-06
Thiram	6.61E-08
Benomyl	3.72E-08

1.2 Life cycle inventory of Oil Palm cultivation and data quality considerations

Tab. 6.17 shows the life cycle inventory and the data quality indicators for the cultivation of Oil Palms. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 6.17 Unit process raw data for the cultivation of Oil Palms

401	InputGroup	OutputGroup	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	palm fruit bunches, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location						MY			
493			InfrastructureProcess						0			
403			Unit						kg			
	-	0	palm fruit bunches, at farm	MY	-	-	0	kg	1.00E+0			
resource, in air	4	-	Carbon dioxide, in air	-	resour	in air	-	kg	1.15E+0	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	resour	biotic	-	MJ	1.60E+1	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
resource, in ground	4	-	Carbon, in organic matter, in soil	-	resour	in ground	-	kg	2.58E-2	1	1.24	(4,3,1,1,1,4); from the deforestation
technosphere	5	-	ammonium sulphate, as N, at regional storehouse	RER	-	-	0	kg	6.30E-3	1	1.62	(3,2,1,1,1,3); Average of several references
	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	1.28E-3	1	1.62	(3,2,1,1,1,3); Average of several references
	5	-	potassium chloride, as K2O, at regional storehouse	RER	-	-	0	kg	9.46E-3	1	1.62	(3,2,1,1,1,3); Average of several references
	5	-	dolomite, at plant	RER	-	-	0	kg	3.24E-3	1	1.62	(3,2,1,1,1,3); Average of several references
	5	-	lime, from carbonation, at regional storehouse	CH	-	-	0	kg	1.72E-3	1	1.62	(3,2,1,1,1,3); Average of several references
	5	-	irrigating	CH	-	-	0	ha	7.01E-5	1	1.14	(2,3,2,1,1,4); Corley 2003
	5	-	phenoxy-compounds, at regional storehouse	RER	-	-	0	kg	5.84E-6	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	organophosphorus-compounds, at regional storehouse	RER	-	-	0	kg	4.05E-5	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	[thio]carbamate-compounds, at regional storehouse	RER	-	-	0	kg	2.04E-5	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	pyretroid-compounds, at regional storehouse	CH	-	-	0	kg	2.88E-6	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	benzimidazole-compounds, at regional storehouse	RER	-	-	0	kg	3.72E-8	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	pesticide unspecified, at regional storehouse	RER	-	-	0	kg	1.14E-7	1	1.09	(2,2,1,1,1,3); Tenaganita 2002
	5	-	fertilising, by broadcaster	CH	-	-	0	ha	3.36E-5	1	1.14	(2,3,2,1,1,4); Corley 2003
	5	-	application of plant protection products, by field sprayer	CH	-	-	0	ha	3.36E-5	1	1.14	(2,3,2,1,1,4); Corley 2003
	5	-	wood chopping, mobile chopper, in forest	RER	-	-	0	kg	1.09E+0	1	1.53	(2,3,2,3,4,4); Corley 2003
	5	-	transport, tractor and trailer	CH	-	-	0	tkm	1.27E-3	1	2.09	(4,5,na,na,na,na); Corley 2003
	5	-	transport, lorry 32t	RER	-	-	0	tkm	7.61E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, freight, rail	RER	-	-	0	tkm	2.64E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	provision, stubbed land	MY	-	-	0	m2	1.60E-2	1	1.05	(1,1,1,1,1,1); FAOSTAT 2006
resources	4	-	Transformation, from forest, intensive, clear-cutting	-	resour	land	-	m2	1.60E-2	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006
resources	4	-	Transformation, to forest, intensive, short-cycle	-	resour	land	-	m2	1.60E-2	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006
	4	-	Occupation, forest, intensive, short-cycle	-	resour	land	-	m2a	4.48E-1	1	1.50	(1,1,1,1,1,1); FAOSTAT 2006
emission air, low population density	-	4	Ammonia	-	air	low population density	-	kg	5.04E-4	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	air	low population density	-	kg	2.18E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	air	low population density	-	kg	4.58E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Carbon dioxide, land transformation	-	air	low population density	-	kg	9.45E-2	1	1.49	(4,3,1,1,1,4); Carbon loss from soil after deforestation
emission water, river	-	4	Phosphorus	-	water	river	-	kg	7.79E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	water	ground-	-	kg	2.80E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrate	-	water	ground-	-	kg	5.58E-3	1	1.58	(4,3,1,1,1,4); Estimation
emission agricultural soil	-	4	Cadmium	-	soil	agricultural	-	kg	1.45E-9	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Chromium	-	soil	agricultural	-	kg	5.85E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Copper	-	soil	agricultural	-	kg	-3.83E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Nickel	-	soil	agricultural	-	kg	7.69E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Lead	-	soil	agricultural	-	kg	7.48E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Zinc	-	soil	agricultural	-	kg	-4.22E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	2,4-D	-	soil	agricultural	-	kg	5.84E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Glyphosate	-	soil	agricultural	-	kg	4.05E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Carbufuran	-	soil	agricultural	-	kg	2.04E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Cypermethrin	-	soil	agricultural	-	kg	2.88E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Thiram	-	soil	agricultural	-	kg	6.61E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Benomyl	-	soil	agricultural	-	kg	3.72E-8	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application

6.14 Cumulative Results and Interpretation

6.14.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

6.14.2 Cultivation of oil palms

Tab. 6.18 shows selected LCI results and the cumulative energy demand for the cultivation of Oil Palms.

Tab. 6.18 Selected LCI results and the cumulative energy demand for the cultivation of Oil Palms

		Name		palm fruit bunches, at farm
c		Location		MY
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	2.8
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.5
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	16.0
LCI results				
resource	Land occupation	total	m2a	4.6E-1
air	Carbon dioxide, fossil	total	kg	5.9E-2
air	NMVOC	total	kg	1.6E-3
air	Nitrogen oxides	total	kg	5.3E-4
air	Sulphur dioxide	total	kg	2.3E-4
air	Particulates, < 2.5 um	total	kg	9.1E-4
air	Dinitrogen monoxide	total	kg	2.4E-4
air	Methane, fossil	total	kg	7.7E-4
water	BOD	total	kg	1.6E-4
soil	Cadmium	total	kg	1.6E-9
water	Phosphorus	total	kg	2.8E-6
water	Nitrate	total	kg	5.6E-3
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-1.1E+0
air	Carbon dioxide, land transformation	low population density	kg	2.5E-1
air	Methane, biogenic	total	kg	4.5E-7
air	Carbon monoxide, biogenic	total	kg	2.1E-6

Tab. 6.19 shows a comparision of the CED with values found in literature from three companies in Brazil and three companies in Columbia. Because in the literature source, which has been used (da

Costa et al. 2006) the different inputs of the palm cultivation are not described, it is not possible to say, where the differences come from. The plantations in Brazil are not irrigated, which has an important influence on the CED value.

Tab. 6.19 Comparison of some results

	CED, non-renewable energy resources, fossil + nuclear (MJ-Eq)
Palm fruit bunches, at farm, MY	1.5
Brazil, Company A [1]	0.0011
Brazil, Company B [1]	0.0057
Brazil, Company C [1]	0.0025
Columbia, Company A [1]	0.23
Columbia, Company B [1]	0.28
Columbia, Company C [1]	0.15

1: Source: da Costa et al. 2006

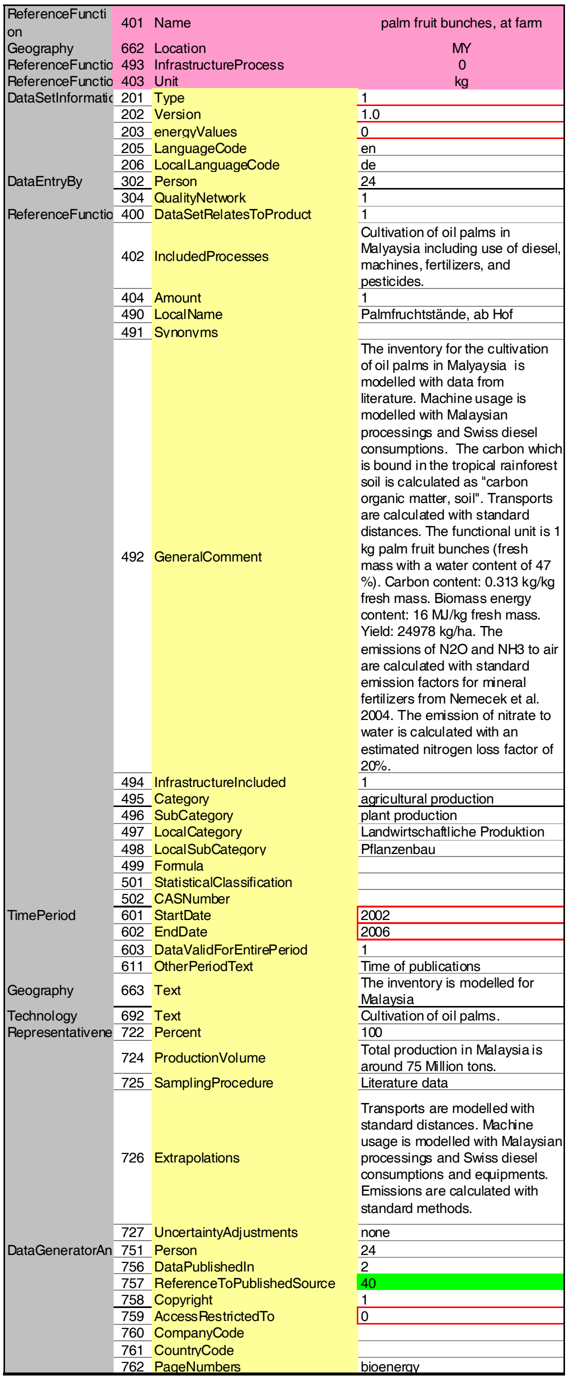
6.15 Conclusions

The life cycle inventory for the oil palm cultivation in Malaysia is determined largely by the transformation of tropical rain forests to palm plantations. For further work more information about machine usage and recultivation of palm plantation should be included. The emissions of N2O, NOx and NH3 to air and of nitrate and phosphorus to water should be calculated with a better model. Further improvements can be achieved if the oil palm cultivation in Indonesia is included.

Abbreviations

dm:	dry matter
FFB:	fresh fruit bunches
fm:	fresh matter

Appendix: EcoSpold Meta Information



ReferenceFunction	401	Name	palm fruit bunches, at farm
Geography	662	Location	MY
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of oil palms in Malyaysia including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1
	490	LocalName	Palmfruchtstände, ab Hof
	491	Synonyms	
	492	GeneralComment	The inventory for the cultivation of oil palms in Malyaysia is modelled with data from literature. Machine usage is modelled with Malaysian processings and Swiss diesel consumptions. The carbon which is bound in the tropical rainforest soil is calculated as "carbon organic matter, soil". Transports are calculated with standard distances. The functional unit is 1 kg palm fruit bunches (fresh mass with a water content of 47 %). Carbon content: 0.313 kg/kg fresh mass. Biomass energy content: 16 MJ/kg fresh mass. Yield: 24978 kg/ha. The emissions of N2O and NH3 to air are calculated with standard emission factors for mineral fertilizers from Nemecek et al. 2004. The emission of nitrate to water is calculated with an estimated nitrogen loss factor of 20%.
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2002
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications
Geography	663	Text	The inventory is modelled for Malaysia
Technology	692	Text	Cultivation of oil palms.
Representativene	722	Percent	100
	724	ProductionVolume	Total production in Malaysia is around 75 Million tons.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances. Machine usage is modelled with Malaysian processings and Swiss diesel consumptions and equipments. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	bioenergy

References

Achard et al. 2002	Achard, F., H. D. Eva, H. J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J. P. Malingreau (2002): Determination of deforestation rates of the world's humid tropical forests. Science 297: 999–1002.
Corley 2003	Corley, R., Tinker, P. (Ed.): The Oil Palm. World Agriculture Series. Blackwell Science. Oxford 2003
CSPI 2005	Center for Science in the Public Interest: Cruel Oil. How Palm Oil Harms Health, Rainforest & Wildlife. Washington 2005

Da Costa et al. 2006	da Costa, R., Silva Lora, E.: The energy banace in the production of palm oil diesel – two case studies: Brazil and Columbia. Federal University of Itajubá/Excellence Group in Thermal and Distributed Generation NEST (IEM/UNIFEI) 2006. Retrieved 14. September 2006, from http//www.svebio.se/attachments/33/295.pdf
FAOSTAT 2006	Faostat Database Query: Oil palm Production. Retrieved 16. May 2006, from http://faostat.fao.org/faostat/
Fearnside 2000	Fearnside, P. M. (2000): Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46: 115–158
Frischknecht et al. 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Hofstetter 2006	Hofstetter, Patrick: Personal communication. WWF Switzerland. June 2006
Houghton et al. 2000	Houghton, R. A., D. L. Skole, C. A. Nobre, J. L. Hackler, K. T. Lawrence, and W. H. Chomentowski (2000): Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. Nature., 403, 301–304.
IFA 2006	IFA (2006): World Fertilizer Use Manual. Retrieved 16. May 2006, from http://www.fertilizer.org/ifa
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch
Ng et al. 1999	Ng, P.H.C., Chew P.S., Goh K.J. & Kee K.K. (1999): Nutrient requirements and sustainability in mature Oil Palms - an assessment. Planter, Kuala Lumpur 75: 331-345
Ostermayer 2002	Ostermayer, Axel: Ökobilanz für DL-Methionin in der Geflügelmast. Endbericht im Auftrag der Degussa AG. Institut für Energie- und Umweltforschung Heidelberg, Heidelberg 2002
Tenaganita 2002	Tenaganita and Pesticide Action Network (PAN) Asia and The Pacific: Poisened and Silenced. A Study of pesticide poisening in the Plantations. 2002
USDA 2004	United States Department of Agriculture (2004): Malaysia: Below-Normal Rainfall May Limit Palm Oil Yields Late 2004-Early 2005. Production Estimates and Crop Assessment Division. Foreign Agricultural Service
Werner et al. 2003	Werner F., Althaus H.-J., Künniger T., Richter K. and Jungbluth N. (2003) Life Cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent 2000 No. 9. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.

7 Rape, conventional production in Germany

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7.1 Introduction

Rape (*Brassica napus* L.), also known as Rapeseed or Oilseed Rape, is a yellow-flowered member of the family *Brassicaceae*.

Rapeseed is very widely cultivated throughout the world for the production of animal feed, vegetable oil for human consumption, and biodiesel. The leading producers include the European Union, Canada, the United States, Australia, China and India (FAOSTAT 2006).

The functional unit is 1 kg of rape (fresh matter), at farm, DE. The properties of rape are given in Tab. 7.1.

Tab. 7.1 Properties of rape (Nemecek et al. 2004)

Property	Value	Unit
Water	0.06	kg/kg rape fresh matter
Carbon content	0.73	kg/kg rape fresh matter
HHV	27.8	MJ/kg rape fresh matter
Cd	1.6	mg/kg rape dry matter
Cr	0.5	mg/kg rape dry matter
Cu	3.3	mg/kg rape dry matter
Pb	5.25	mg/kg rape dry matter
Ni	2.6	mg/kg rape dry matter
Zn	48	mg/kg rape dry matter

7.2 Yields

In Tab. 7.2 values for the area and the yields of rape cultivation in Germany are given. The yield, which is used in this study, is based on an average over the last five years to adjust annual deviations. The data are based on official statistics and represent 100 % of the German rape cultivation.

Tab. 7.2 Area with rape cultivation in the years 2001 – 2005 in Germany (ha) (FAOSTAT 2006)

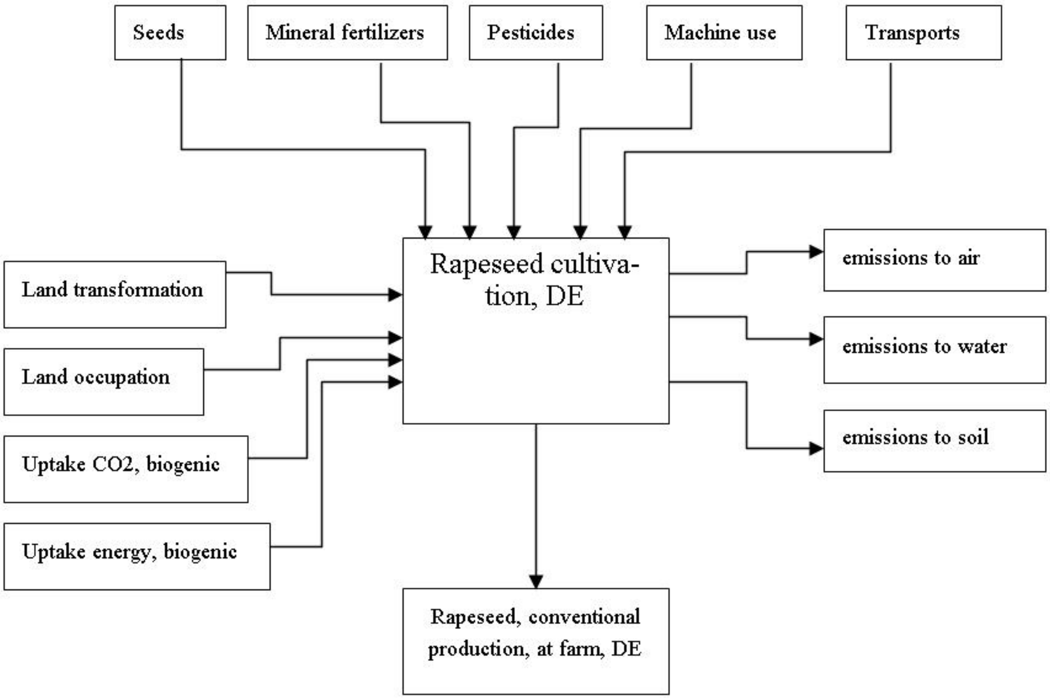
Year	area (ha)	yield (kg/ha)
2001	1137962	3656
2002	1296648	2968
2003	1268000	2869
2004	1283400	4111
2005	1345300	3463
Average (used in this study)	1266262	3413

7.3 System Characterisation

This report corresponds to the dataset of the production of **1 kg rape seed, conventional production, in Germany**.

All data in the present report are referred to 1 kg rape seed (fresh matter). The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

Fig. 7.1 Process flow chart for the cultivation of rape in Germany



7.4 Raw materials and auxiliaries

1.2.1 Fertilizers

KTBL (2004) reports quantities for fertilizer use in Germany for different yields. The data are based on average consumptions of representative farms. From these data values for average fertilizer use in Germany are calculated with the yield of 3413 kg/ha, which is used in this study. They are given in Tab. 7.3.

For the neutralization of the pH value in the soil KTBL (2004) reports an amount of 1000 kg lime used per ha and year

Tab. 7.3 Fertilizer use in the rape cultivation in Germany (KTBL 2004)

Yield [t]	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]
2.5	180	100	230
3	210	112.5	250
3.5	230	125	270
3.413 (This study)	238.9	128	284.3

Kaltschmidt et al. (1997) reports proportions for the different fertilizer products from the German trade statistics in 1993/94. They are given in Tab. 7.4.

Tab. 7.4 Fertilizer use by product in Germany

Nutrient	Product	Use by product in Germany (%) (Kaltschmidt et al. 1997)	Nutrient content (%) (Nemecek et al. 2004)
N	Calcium ammonium nitrate	62.8	27
	Urea	10.3	46
	Ammonium nitrate	13	35
	Ammonium nitrate phosphate	6.9	8
	MAP/DAP	6.9	46
P2O5	SSP	14.2	21
	TSP	42.6	48
	MAP/DAP	21.6	46
	Ammonium nitrate phosphate	21.6	52
K2O	Potassium chloride	48	60
	Potassium nitrate	52	44

Tab. 7.5 Use of fertilizers in the cultivation of rape in this study

Product	kg kg^{-1} rape seed
calcium ammonium nitrate as N	4.173E-02
urea as N	6.845E-03
ammonium nitrate as N	8.639E-03
ammonium nitrate phosphate as N	4.585E-03
diammonium phosphate as N	4.585E-03
single superphosphate as P2O5	5.055E-03
triple superphosphate as P2O5	1.517E-02
diammonium phosphate as P2O5	7.689E-03
ammonium nitrate phosphate as P2O5	7.689E-03
potassium chloride as K2O	3.796E-02
potassium nitrate as K2O	4.112E-02
lime from carbonation	2.930E-01

1.2.2 Pesticides and Biological Control

Roßberg et al. (2002) reports amounts of pesticides used in the rape cultivation in Germany. The data are based on the average consumptions of around 1000 farms in Germany, which represent about 4 % of the cultivated area in Germany. The values for the pesticide use are given here.

Tab. 7.6 Pesticides use in the rape cultivation (Roßberg et al. 2003)

Pesticide group	Pesticide	Amount [g/ha/y]	Used dataset
Fungicides	Carbendazim	12.3624	Benzimidazole-compounds
	Metconazol	17.3196	Cyclic N-compounds
	Prochloraz	4.7736	Cyclic N-compounds
	Tebuconazol	55.624	Cyclic N-compounds
	Vinclozolin	17.34	Phenoxy-compounds
	Iprodion	0.004284	Benzimidazole-compounds
	Thiophanat-methyl	18.615	Benzimidazole-compounds
Herbicides	Glyphosate	27.69932	Glyphosate
	Metazachlor	474.95	Pesticides, unspecific
	Quinmerac	59.295	Pesticides, unspecific
	Clomazon	1.08324	Cyclic N-compounds
	Propaquizafop	25.665	Diphenylether-compounds
	Dimethachlor	51.08928	Pesticides, unspecific
	Trifluralin	81.5616	Dinitroaniline-compounds
	Napropamid	35.60768	Acetamide-anilide-compounds
	Quizalofop-P	2.28625	Pesticides, unspecific
	Fluazifop-P	11.0625	Diphenylether-compounds
Insecticides	Cypermethrin	13.3488	Pyretroid-compounds
	Deltamethrin	1.836	Pesticides, unspecific
	alpha-Cypermethrin	69.552	Pyretroid-compounds
	lambda-Cyhalothrin	1.2852	Pyretroid-compounds
	beta-Cyfluthrin	3.096	Pesticides, unspecific
	tau-Fluvalinat	1.86624	Pesticides, unspecific
Grow regulator	Chlormequat	128.5632	Pesticides, unspecific
	Trinexapac	0.63936	Pesticides, unspecific

Tab. 7.7 Use of pesticides in the cultivation of rape in this study

Product	kg kg^{-1} rape
Benzimidazole-compounds	9.078E-06
Cyclic N-compounds	2.309E-05
Phenoxy-compounds	5.081E-06
Glyphosate	8.116E-06
Diphenylether-compounds	1.076E-05
Dinitroaniline-compounds	3.433E-05
Acetamide-anilide-compounds	2.467E-05
Pyretroid-compounds	2.12E-04
Pesticides, unspecific	9.078E-06

1.2.3 Seed

About 3.5 kg seeds per ha are used (Nemecek et al. 2004). The use of the seeds is calculated with the dataset “rapeseed IP, at regional storehouse, CH” from Nemecek et al. (2004).

7.5 Energy and machine usage

Cultivation

KTBL (2004) reports data on the machine use, the processings and the diesel consumption of cultivation of rape. The values are based on average consumptions of representative farms. The values, which are used for the processes, are calculated from the diesel use of the field work datasets in Nemecek et al. (2004).

Tab. 7.8 Machine use in the rape cultivation

Process	Diesel consumption in the field works in the rape cultivation in Germany (KTBL 2004)	Diesel consumption in the field work datasets in Nemecek et al. (2004)	Machine use in rape cultivation in Germany
	[l/ha/y]	[kg/ha/y]	[ha/kg rape]
fertilizing	6.48	5.29	3.385E-04
ploughing	23.06	26.11	2.440E-04
harrowing	11.35	4.44	7.064E-04
sowing	3.22	3.82	2.327E-04
application plant protection	4.30	1.76	6.744E-04
combine harvesting	18.65	33.31	1.547E-04
Chiseling	15.78	15.52	2.810E-04
Together	82.8		

7.6 Transportation

Kaltschmidt et al. (1997) reports transport distances for rape from field to farm in Germany. These values are used in this study. For the transports to the farm the standard distances, which are given in Nemecek et al. (2004), are used. Pesticides and fertilizers are converted into the product weight in order to calculate the requirements for transports in tkm. For pesticides a mean active-ingredient content of 50 % is used according to Nemecek et al. (2004). For the fertilizers the average nutrient contents are used, which are given in Tab. 7.4.

Tab. 7.9 Transports distances in the rape cultivation

Material	Tractor and trailer [km]	Lorry 32t [km]	Rail [km]	Barge [km]	Remarks
Seeds	15	-	-	-	Nemecek et al. 2004
N-Fertilizers		100	100	900	Nemecek et al. 2004
P-Fertilizers		100	100	400	Nemecek et al. 2004
K-Fertilizers		100	100	100	Nemecek et al. 2004
Pesticides	15	-	-	-	Nemecek et al. 2004
Limestone	15				Nemecek et al. 2004
rape	10	-	-		Kaltschmidt et al. 1997

Tab. 7.10 Total transport services for the rape cultivation in Germany

Material	Rape cultivation in Germany
lorry 28t [tkm]	5.053E-02
rail [tkm]	5.053E-02
barge [tkm]	2.858E-01
tractor and trailer [tkm]	1.6E-02

7.7 Drying

The drying of rape seeds is calculated with the dataset "graindrying, low temperature" according to Nemecek et al. (2004). The rape is dried from 12 % moisture at harvest to 6 % moisture at storage. These values are based on Swiss data (Nemecek et al. 2004) because no data are available for moisture of rape in Germany.

7.8 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account) and the yield per area unit. The land occupied was always considered as "Occupation, arable, non-irrigated", since the land was assumed not to be irrigated.

Land transformation was calculated on the basis of the area required to produce 1 kg of product. The type of use before establishment of the crop was assumed to be 71% arable land and 29 meadow (sown on arable land). These percentages correspond to the proportion of arable crops and leys out of the arable surface in Germany: 11.995.000 ha arable crops (71 %), 4.968.000 ha leys (29 %), arable surface total 16.963.000 ha in 2003, taken from Statistik (2003).

In Tab. 7.11 the accounted amounts of land use are given. They are calculated with a yield of 3.04 t rape per year and ha. The occupation is calculated as permanent for 11 months per year according to the rape cultivation in Switzerland (Nemecek et al. 2004).

Tab. 7.11 Amounts of land use for the cultivation of rape in Germany

Land use	per kg rape
Transformation from arable, not irrigated [m2]	2.08
Transformation from pasture and meadow [m2]	0.85
Transformation to arable, not irrigated [m2]	2.93
Occupation, arable, not irrigated [m2a]	2.69

7.9 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon balance. The carbon content of the seeds is calculated as carbon input. The biomass energy is calculated from the energy content of the rape.

Tab. 7.12 Uptake of CO_2 and biomass energy

	per kg rape fresh matter
CO_2, biogenic [kg]	2.69
Energy, biomass [MJ]	27.8

7.10 Emissions to air

For the emission of NH_3, N_2O, and NO_x to air from the mineral fertilizers the emission factors according to Nemecek et al. (2004) are used:

The NH_3-N emissions are calculated with different emissions factors for the mineral fertilizers: 15 % for urea, 2 % for ammonium nitrate and calcium ammonium nitrate, and 4 % for dap and nk.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that is leached as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

In Tab. 7.13 values for the emissions to air from rape cultivation are given.

Tab. 7.13 Emissions to air from rape cultivation

Emission	Value	Unit	Source
NH_3-N	2.69548E-03	[kg/kg rape]	calculated from the N-input
N_2O	1.699237E-03	[kg/kg rape]	calculated from the N-input and nitrate leaching
NO_x	3.5684E-04	[kg/kg rape]	calculated from the N-input

7.11 Emissions to water

For the phosphorus emissions to water and nitrate leaching to ground water the emission factors are calculated according to the method, which is described in Nemecek et al. (2004) for Switzerland.

Tab. 7.14 Emissions to water from rape cultivation

Emission	Emission factor (% of the nutrient contained in the fertilizers)	Value (kg/kg rape)
Phosphorus, to surface water	0.0576	1.192E-04
Phosphorus, to ground water	0.335	2.051E-05
Nitrate, to ground water	11.75	3.454E-02

7.12 Emissions to soil

The applied pesticides are calculated as emissions to soil. For pesticides, for which no elementary flows are available, comparable substances are used, which belong to the same substance class.

The differences between the inputs of heavy metals contained in the fertilizers and the seeds and the outputs through harvested products are assumed to be heavy metal emissions to soil.

Tab. 7.15 Emissions to soil from rape cultivation

Emission (kg/kg rape)	Value
Cd	5.294E-07
Cr	1.195E-05
Cu	3.100E-06
Pb	2.911E-06
Ni	2.782E-06
Zn	6.865E-05
Carbendazim	3.62E-06
Metconazole	5.07E-06
Prochloraz	1.40E-06
Tebuconazole	1.63E-05
Vinclozolin	5.08E-06
Iprodion	1.26E-09
Thiophanat-methyl	5.45E-06
Glyphosate	8.12E-06
Metazachlor	1.39E-04
Quinmerac	1.74E-05
Clomazone	3.17E-07
Propaquizafop	7.52E-06
Dimethachlor	1.50E-05
Trifluralin	2.39E-05
Napropamide	1.04E-05
Quizalofop-P	6.70E-07
Fluazifop-P-butyl	3.24E-06
Cypermethrin	2.43E-05
Deltamethrin	5.38E-07
Lamda-Cyhalothrin	3.77E-07
Cyfluthrin	9.07E-07
tau-Fluvalinat	5.47E-07
Chlormequat	3.77E-05
Trinexapac-ethyl	1.87E-07

1.3 Life cycle inventory of rape cultivation and data quality considerations

Tab. 7.16 shows the life cycle inventory and the data quality indicators for the cultivation of rape. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 7.16 Unit process raw data for the cultivation of rape

	ID	3503	3504	3702	3703	3506	3507	3508	3706	3707	3708	3709	3792
	401	InputGroup	OutputGroup	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	rape seed conventional, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
	662			Location						DE			
	493			InfrastructureProcess						0			
	403			Unit						kg			
		-	0	rape seed conventional, at farm	DE	-	-	0	kg	1.00E+0			
resource, in air		4	-	Carbon dioxide, in air	-	resoul	in air	-	kg	2.69E+0	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic		4	-	Energy, gross calorific value, in biomass	-	resoul	biotic	-	MJ	2.78E+1	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
technosphere		5	-	rape seed IP, at regional storehouse	CH	-	-	0	kg	1.03E-3	1	1.08	(1,3,1,2,1,2); Nemecek 2004
		5	-	calcium ammonium nitrate, as N, at regional storehouse	RER	-	-	0	kg	4.17E-2	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	urea, as N, at regional storehouse	RER	-	-	0	kg	6.84E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	ammonium nitrate, as N, at regional storehouse	RER	-	-	0	kg	8.64E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	ammonium nitrate phosphate, as N, at regional storehouse	RER	-	-	0	kg	4.59E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	diammonium phosphate, as N, at regional storehouse	RER	-	-	0	kg	4.59E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	single superphosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	5.06E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	triple superphosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	1.52E-2	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	ammonium nitrate phosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	7.69E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	7.69E-3	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	potassium chloride, as K2O, at regional storehouse	RER	-	-	0	kg	3.80E-2	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	potassium nitrate, as K2O, at regional storehouse	RER	-	-	0	kg	4.11E-2	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	lime, from carbonation, at regional storehouse	CH	-	-	0	kg	2.93E-1	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	benzimidazole-compounds, at regional storehouse	RER	-	-	0	kg	9.08E-6	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	cyclic N-compounds, at regional storehouse	RER	-	-	0	kg	2.31E-5	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	phenoxy-compounds, at regional storehouse	RER	-	-	0	kg	5.08E-6	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	glyphosate, at regional storehouse	RER	-	-	0	kg	8.12E-6	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	diphenylether-compounds, at regional storehouse	RER	-	-	0	kg	1.08E-5	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	dinitroaniline-compounds, at regional storehouse	RER	-	-	0	kg	3.43E-5	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	pyretroid-compounds, at regional storehouse	CH	-	-	0	kg	2.47E-5	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	pesticide unspecified, at regional storehouse	RER	-	-	0	kg	2.12E-4	1	1.07	(1,3,1,1,1,1); Rossberg 2003
		5	-	fertilising, by broadcaster	CH	-	-	0	ha	3.18E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	tillage, ploughing	CH	-	-	0	ha	2.29E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	tillage, harrowing, by spring tine harrow	CH	-	-	0	ha	6.63E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	sowing	CH	-	-	0	ha	2.18E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	application of plant protection products, by field sprayer	CH	-	-	0	ha	6.33E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	combine harvesting	CH	-	-	0	ha	1.45E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	tillage, cultivating, chiselling	CH	-	-	0	ha	2.64E-4	1	1.07	(1,3,1,1,1,2); KTBL 2004
		5	-	grain drying, low temperature	CH	-	-	0	kg	6.82E-2	1	1.09	(1,3,1,3,1,3); Nemecel 2004
		5	-	transport, lorry 28t	CH	-	-	0	tkm	5.05E-2	1	2.09	(4,5,na,na,na,na); Nemecel 2004
		5	-	transport, freight, rail	RER	-	-	0	tkm	5.05E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
		5	-	transport, barge	RER	-	-	0	tkm	2.86E-1	1	2.09	(4,5,na,na,na,na); Standard Distances
		5	-	transport, tractor and trailer	CH	-	-	0	tkm	1.50E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
resources		4	-	Transformation, from arable, non-irrigated	-	resoul	land	-	m2	2.08E+0	1	2.00	(1,1,1,1,1,1); Statistics 2001-2005
		4	-	Transformation, from pasture and meadow	-	resoul	land	-	m2	8.50E-1	1	2.00	(1,1,1,1,1,1); Statistics 2001-2005
		4	-	Transformation, to arable, non-irrigated	-	resoul	land	-	m2	2.93E+0	1	2.00	(1,1,1,1,1,1); Statistics 2001-2005
		4	-	Occupation, arable, non-irrigated	-	resoul	land	-	m2a	2.69E+0	1	1.50	(1,1,1,1,1,1); Statistics 2001-2005
emission air, low population density		-	4	Ammonia	-	air	low population density	-	kg	2.40E-3	1	1.32	(4,3,1,1,1,4); Calculated with standard method
		-	4	Dinitrogen monoxide	-	air	low population density	-	kg	1.69E-3	1	1.58	(4,3,1,1,1,4); Calculated with standard method
		-	4	Nitrogen oxides	-	air	low population density	-	kg	3.56E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, river		-	4	Phosphorus	-	water	river	-	kg	1.19E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, ground		-	4	Phosphorus	-	water	ground-	-	kg	2.05E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
		-	4	Nitrate	-	water	ground-	-	kg	3.45E-2	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission agricultural soil		-	4	Cadmium	-	soil	agricultural	-	kg	5.29E-7	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Chromium	-	soil	agricultural	-	kg	1.20E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Copper	-	soil	agricultural	-	kg	3.10E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Nickel	-	soil	agricultural	-	kg	2.91E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Lead	-	soil	agricultural	-	kg	2.78E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Zinc	-	soil	agricultural	-	kg	6.87E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
		-	4	Carbendazim	-	soil	agricultural	-	kg	3.62E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Metconazole	-	soil	agricultural	-	kg	5.07E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Prochloraz	-	soil	agricultural	-	kg	1.40E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Tebuconazole	-	soil	agricultural	-	kg	1.63E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Vinclozolin	-	soil	agricultural	-	kg	5.08E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Iprodion	-	soil	agricultural	-	kg	1.26E-9	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Thiophanat-methyl	-	soil	agricultural	-	kg	5.45E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Glyphosate	-	soil	agricultural	-	kg	8.12E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Metazachlor	-	soil	agricultural	-	kg	1.39E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Quinmerac	-	soil	agricultural	-	kg	1.74E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Clomazone	-	soil	agricultural	-	kg	3.17E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Propaquizafop	-	soil	agricultural	-	kg	7.52E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Dimethachlor	-	soil	agricultural	-	kg	1.50E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Trifluralin	-	soil	agricultural	-	kg	2.39E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Napropamide	-	soil	agricultural	-	kg	1.04E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Quizalofop-P	-	soil	agricultural	-	kg	6.70E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Fluazifop-P-butyl	-	soil	agricultural	-	kg	3.24E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Cypermethrin	-	soil	agricultural	-	kg	2.43E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Deltamethrin	-	soil	agricultural	-	kg	5.38E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Lamda-Cyhalothrin	-	soil	agricultural	-	kg	3.77E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Cyfluthrin	-	soil	agricultural	-	kg	9.07E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	tau-Fluvalinate	-	soil	agricultural	-	kg	5.47E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Chlormequat	-	soil	agricultural	-	kg	3.77E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
		-	4	Trinexapac-ethyl	-	soil	agricultural	-	kg	1.87E-7	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application

7.13 Cumulative Results and Interpretation

1.3.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

1.3.2 Cultivation of rape

Tab. 7.17 shows selected LCI results and the cumulative energy demand for the cultivation of rape in Germany in comparison to the ecoinvent dataset rape seed, IP, at farm, CH. The results are comparable. Only the CED, the N_2O-emissions, and the nitrate-emissions are remarkable higher in the German production, which is due to the higher N-fertilizer use (126 kg N/ha in Switzerland, 238.9 kg N/ha in Germany). The pesticides emissions are higher in the Swiss production.

Tab. 7.17 Selected LCI results and the cumulative energy demand for the cultivation of rape

		Name		rape seed conventional, at farm	rape seed IP, at farm
		Location		DE	CH
		Unit	Unit	kg	kg
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	8.5	5.5
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.2	0.8
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.3	0.3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	28.0	25.0
LCI results					
resource	Land occupation	total	m2a	2.8E+0	2.9E+0
air	Carbon dioxide, fossil	total	kg	4.9E-1	3.3E-1
air	NMVOC	total	kg	4.6E-4	4.0E-4
air	Nitrogen oxides	total	kg	3.2E-3	2.6E-3
air	Sulphur dioxide	total	kg	1.6E-3	7.1E-4
air	Particulates, < 2.5 um	total	kg	2.8E-4	2.4E-4
air	Dinitrogen monoxide	total	kg	2.7E-3	1.7E-3
air	Methane, fossil	total	kg	8.9E-4	5.1E-4
water	BOD	total	kg	1.2E-3	9.6E-4
soil	Cadmium	total	kg	5.3E-7	-7.5E-7
water	Phosphorus	total	kg	2.1E-5	9.9E-9
water	Nitrate	total	kg	3.5E-2	1.7E-2
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	-2.7E+0	-2.7E+0
air	Carbon dioxide, land transformation	low population density	kg	8.9E-5	1.8E-5
air	Methane, biogenic	total	kg	2.9E-6	1.2E-6
air	Carbon monoxide, biogenic	total	kg	2.7E-5	3.9E-5

7.14 Conclusions

The life cycle inventory for the rape cultivation in Germany is determined largely by the fertilizer usage. For further work the emissions of N_2O, NOx and NH_3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	rape seed conventional, at farm
Geography	662	Location	DE
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of rape in Germany including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1
	490	LocalName	Raps konventionell, ab Hof
	491	Synonyms	
	492	GeneralComment	The inventory for the cultivation of rape in Germany is modelled with data from literature. The functional unit is 1 kg rapeseed (fresh mass with a water content of 6 %). Carbon content: 0.73 kg/kg fresh mass. Biomass energy content: 27.8 MJ/kg fresh mass. Yield: 3413 kg/ha. The emissions of N2O and NH3 to air are calculated with standard factors from Nemecek et al. 2004. The emission of nitrate to water is calculated according to the method, which is described in Nemecek et al. 2004 for Swiss rape production.
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1996
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications. Data for the fertilizers products and the transport distance to the farm are from 1996. Data for the pesticide use are from 2001. Data for the yield and lkand use are from 2006.
Geography	663	Text	The inventory is modelled for Germany
Technology	692	Text	Conventional production
Representativene	722	Percent	100
	724	ProductionVolume	Total production in Germany is around 416000 tons.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	bioenergy

References

FAOSTAT 2006	Faostat Database Query: Rape Production. Retrieved 16. May 2006, from http://faostat.fao.org/faostat/
Frischknecht et al. 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent

	2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Kaltschmidt et al. 1997	Kaltschmitt, M. & Reinhardt, G. (1997): Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung. Verlag Vieweg, Braunschweig/Wiesbaden.
KTBL 2004	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.: Betriebsplanung Landwirtschaft 2004/2005 – Daten für die Betriebsplanung in der Landwirtschaft. 20. Auflage. Darmstadt
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Roßberg et al. 2002	Roßberg, D./Gutsche, V./Enzian, S./Wick, M. (2002): Neptun 2000 - Erhebung von Daten zum tatsächlichen Einsatz chemischer Pflanzenschutzmittel im Ackerbau Deutschlands. Berichte aus der Biologischen Bundesanstalt für Land- und Forstwirtschaft Heft 98

8 Rye, production in Europe

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8.1 Introduction

Rye (*Secale cereale* L.) is a cereal of the family *Poaceae*. It is the most important bread cereal in Middle and Eastern Europe (FAOSTAT 2006).

For this inventory the functional unit is 1 ha of rye cultivation, RER. This is a multi-output process with rye grains and rye straw as allocated products. The properties of rye grains are given in Tab. 8.1 and the properties of rye straw are given in Tab. 8.2.

Tab. 8.1 Properties of rye grains (Nemecek et al. 2004)

Property	Value	Unit
Water	0.15	kg/kg rye grains fresh matter
Carbon content	0.36	kg/kg rye grains fresh matter
HHV	13.43	MJ/kg rye grains fresh matter
Cd	0.026	mg/kg rye grains fresh matter
Cr	0.39	mg/kg rye grains fresh matter
Cu	4.35	mg/kg rye grains fresh matter
Pb	0.435	mg/kg rye grains fresh matter
Ni	0.69	mg/kg rye grains fresh matter
Zn	42.6	mg/kg rye grains fresh matter

Tab. 8.2 Properties of rye straw (Nemecek et al. 2004)

Property	Value	Unit
Water	0.15	kg/kg straw fresh matter
Carbon content	0.37	kg/kg straw fresh matter
HHV	13.86	MJ/kg straw fresh matter
Cd	0.026	mg/kg straw fresh matter
Cr	0.39	mg/kg straw fresh matter
Cu	4.35	mg/kg straw fresh matter
Pb	0.435	mg/kg straw fresh matter
Ni	0.69	mg/kg straw fresh matter
Zn	42.6	mg/kg straw fresh matter

8.2 Yields

Ollier (2006) reports data for the production of rye in the European Union. In Tab. 8.3 values for the cultivated area and the grain yields are given. There is a great difference between rye production in

Western Europe and Eastern Europe (e. g. Germany: 5660 kg rye grain per ha, Poland: 1349 kg per ha). With the production of 1 kg rye grains 1.36 kg straw is produced (Nemecek et al. 2004). According to Nemecek et al. (2004) only 50 % of the straw is harvested, the other 50 % remain on the field.

In this study the yield is calculated with the average value of 3172 kg grains and 2163 kg straw per ha. The yield, which is used in this study, is based on an average over the last five years to adjust annual deviations.

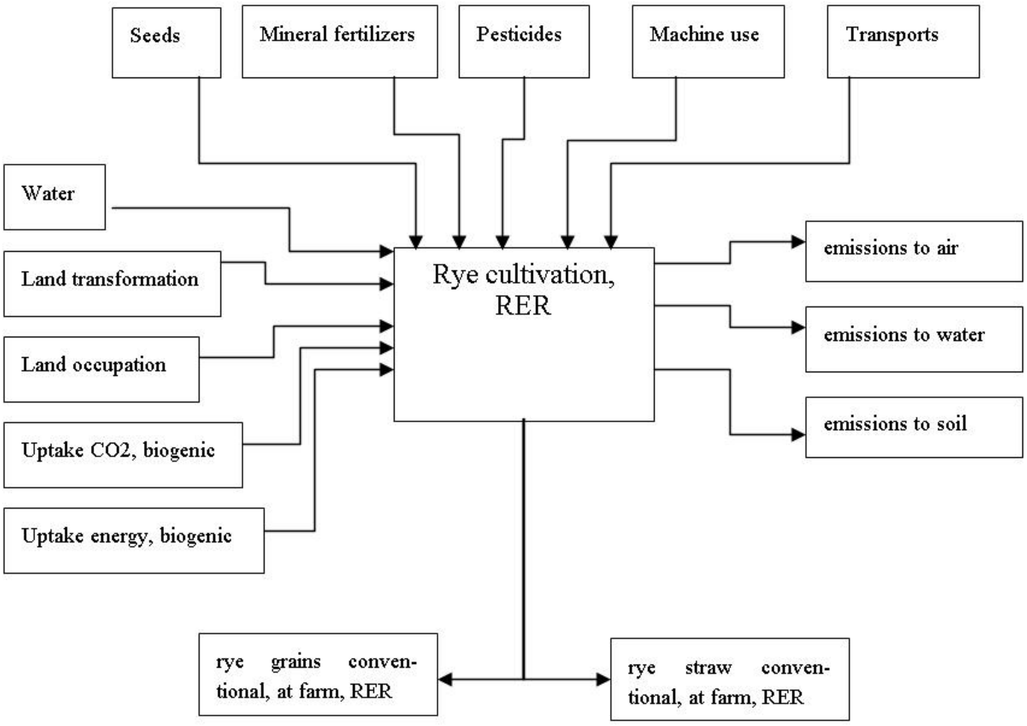
Tab. 8.3 Rye (grains) production in the European Union (Ollier 2006)

Region	Area (1000 ha)	Yield (t/ha*a)
2005	2500	3.04
2004	2821	3.63
2003	2673	2.68
2002	2994	3.16
2001	3627	3.35
Average over 5 years		3.172

8.3 System Characterisation

This report corresponds to the dataset for the cultivation of **1 ha rye, conventional, in Europe**.

Fig. 8.1 Process flow chart for the cultivation of rye in Europe



All data in the present report refer to 1 ha rye cultivation. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of the raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

8.4 Raw materials and auxiliaries

1.3.3 Fertilizers

KTBL (2004) reports quantities for fertilizer use for different yields. From these data values for average fertilizer use are calculated. They are given in Tab. 8.4.

Tab. 8.4 Fertilizer use in the rye cultivation (KTBL 2004)

Yields [kg/ha/y]	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]
1000	40	27.5	65
2000	60	40	85
3000	80	52.5	105
4000	100	65	125
5000	120	77.5	145
6000	140	90	165
7000	160	102.5	185
3172 (this study)	83.4	54.7	108.4

Kaltschmidt et al. (1997) reports proportions for the different fertilizer products from the German trade statistics in 1993/94. They are given in Tab. 8.5.

Tab. 8.5 Fertilizer use by product in Germany (Kaltschmidt et al. 1997)

Nutrient	Product	%
N	Calcium ammonium nitrate	62.8
	Urea	10.3
	Ammonium nitrate	13
	Ammonium nitrate phosphate	6.9
	MAP/DAP	6.9
P2O5	SSP	14.2
	TSP	42.6
	MAP/DAP	21.6
	Ammonium nitrate phosphate	21.6
K2O	Potassium chloride	48
	Potassium nitrate	52

Tab. 8.6 Use of fertilizers in the cultivation of rye in this study (KTBL 2004)

Product	kg ha^{-1}
calcium ammonium nitrate as N	52.4
urea as N	8.59
ammonium nitrate as N	10.85
ammonium nitrate phosphate as N	5.76
diammonium phosphate as N	5.76
single superphosphate as P2O5	7.76
triple superphosphate as P2O5	23.28
diammonium phosphate as P2O5	11.80
ammonium nitrate phosphate as P2O5	11.80
potassium chloride as K2O	52.05
potassium nitrate as K2O	56.39
lime from carbonation	1000

Limestone

KTBL (2004) reports an amount of 1000 kg lime per ha and year for the neutralization of the pH value in the soil.

1.3.4 Pesticides and Biological Control

Roßberg et al. (2002) reports amounts of pesticides use in the rye cultivation in Germany. These data are used for this study. They are given here.

Tab. 8.7 Pesticides use in the rye cultivation (Roßberg et al. 2003)

Pesticide group	Pesticide	Amount [g/ha/y]	Used dataset
Fungicides	Azoxystrobin	22.42009	Pesticides, unspecific
	Carbendazim	5.937457	Benzimidazole-compounds
	Cyproconazol	9.978227	Cyclic N-compounds
	Cyprodinil	11.75122	Cyclic N-compounds
	Dithianon	6.803337	Pesticides, unspecific
	Epoxiconazol	8.890724	Cyclic N-compounds
	Fenbuconazol	1.778145	Pesticides, unspecific
	Fenpropidin	28.2957	Cyclic N-compounds
	Fenpropimorph	56.43677	Cyclic N-compounds
	Fluquinconazol	1.546213	Pesticides, unspecific
	Flusilazol	6.209591	Pesticides, unspecific
	Kresoxim-methyl	10.56579	Pesticides, unspecific
	Metconazol	2.783183	Cyclic N-compounds
	Prochloraz	16.6991	Cyclic N-compounds
	Propiconazol	7.473362	Cyclic N-compounds
	Spiroxamine	51.02502	Pesticides, unspecific
	Tebuconazol	42.46931	Cyclic N-compounds
	Triadimenol	3.736681	Pesticides, unspecific
Herbicides	Amidosulfuron	0.680334	sulfonyl-urea-compounds
	Bentazon	19.3792	benzo(thia)diazole-compounds
	Chlortoluron	18.76072	sulfonyl-urea-compounds
	Cinidon-Ethyl	0.824647	Pesticides, unspecific
	Dichlorprop-P	30.92426	Pesticides, unspecific
	Diflufenican	29.99653	diphenyether-compounds
	Fluroxypyr	2.041001	phenoxy-compounds
	Flurtamone	18.03915	Pesticides, unspecific
	Glyphosat	19.79771	Glyphosate
	Iodosulfuron	0.103081	sulfonyl-urea-compounds
	Ioxynil	36.74833	nitrile-compounds
	Isoproturon	343.2593	Pesticides, unspecific
	MCPA	12.3697	phenoxy-compounds
	Mecoprop-P	16.08061	phenoxy-compounds
	Mefenpyr	0.309243	Pesticides, unspecific
	Metsulfuron	0.190493	sulfonyl-urea-compounds
	Pendimethalin	59.7869	dinitroaniline-compounds
	Thifensulfuron	0.155858	sulfonyl-urea-compounds
	Tribenuron	0.388615	Pesticides, unspecific
Insekticides	Cypermethrin	3.247047	Pyretroid-compounds
	Deltamethrin	0.100504	Pesticides, unspecific
	Dimethoat	70.7547	Pesticides, unspecific
	Esfenvalerat	0.128851	Pesticides, unspecific
	Oxydemeton-methyl	7.211537	Pesticides, unspecific
	Parathion	5.30351	organophosphorus-compounds
	Pirimicarb	3.55629	(thio)carbamate-compounds
	alpha-Cypermethrin	27.11027	Pyretroid-compounds

Pesticide group	Pesticide	Amount [g/ha/y]	Used dataset
	lambda-Cyhalothrin	1.955959	Pyretroid-compounds
Grow regulators	Chlormequat	389.9796	Pesticides, unspecific
	Ethephon	324.0429	Pesticides, unspecific
	Trinexapac	31.30524	Pesticides, unspecific

Tab. 8.8 Use of pesticides in the cultivation of rye in this study

Product	kg ha^1
Benzimidazole-compounds	5.94E-03
Cyclic N-compounds	1.85E-01
sulfonyl-urea-compounds	1.99E-02
benzo(thia)diazole-compounds	1.94E-02
diphenyether-compounds	3.00E-02
phenoxy-compounds	3.05E-02
Glyphosate	1.98E-02
nitrile-compounds	3.67E-02
dinitroaniline-compounds	5.98E-02
Pyretroid-compounds	3.23E-02
organophosphorus-compounds	5.30E-03
(thio)carbamate-compounds	3.56E-03
Pesticides, unspecific	1.31
Total pesticides	1.76

1.3.5 Seed

About 140 kg seeds per ha are used (Nemecek et al. 2004). The use of the seeds is calculated with the dataset “rye seed IP, at regional storehouse, CH” from Nemecek et al. (2004).

8.5 Energy and machine usage

Cultivation

KTBL (2004) reports data for the machine use, the processings and the diesel consumption of the cultivation of rye in Germany. Jungbluth (2006) gives data for the wheat cultivation in Poland. These data are taken also for the rye cultivation because the processings are quite similar. The machine usage for the rye cultivation in Europe is calculated with 45.7 % production in Germany and 54.3 % production in Poland.

Tab. 8.9 Machine use and diesel consumption in the rye cultivation

Process	Diesel consumption In Germany (KTBL 2004)	Diesel consumption In Poland (Jungbluth 2006)	Machine usage in Europe
	[kg/ha/y]	[kg/ha/y]	[ha/ha]
fertilizing	4.56	2.94	6.95E-01
ploughing	19.4	12.5	6.00E-01
harrowing	9.50	6.12	1.73
sowing	2.84	1.83	6.00E-01
application plant protection	3.66	2.36	1.68
combine harvesting	15.9	10.2	3.85E-01
chiseling	13.2	8.53	6.89E-01
Total	69.1	44.5	

The straw is baled (Nemecek et al. 2004).

Tab. 8.10 Other machine usage in the rye cultivation (Nemecek et al. 2004)

Process	Units per ha
Baling	7.22
Loading bales	31.4

8.6 Transportation

For the transports to the farm the standard distances, which are given in Nemecek et al. (2004), are used. Pesticides and fertilizers are converted into the product weight in order to calculate the requirements for transports in tkm. For pesticides a mean active-ingredient content of 50 % is used according to Nemecek et al. (2004). For the fertilizers the average nutrient contents are used, which are given in Nemecek et al. (2004).

Tab. 8.11 Transports distances in the rye cultivation

Material	Tractor and trailer [km]	Lorry 28t [km]	Rail [km]	Barge [km]	Remarks
Seeds	15	-	-		Nemecek et al. 2004
N-Fertilizers		100	100	900	Nemecek et al. 2004
P-Fertilizers		100	100	400	Nemecek et al. 2004
K-Fertilizers		100	100	100	Nemecek et al. 2004
Pesticides	15	-	-	-	Nemecek et al. 2004
Limestone	15	100	600	-	Frischknecht et al. 2003
rye	15	-	-		Nemecek et al. 2004

Tab. 8.12 Transport services caused by supply of raw materials and auxiliaries

Transport service	[tkm per ha]
lorry 28 t	67.7
rail	67.7
barge	370
tractor	49.7

8.7 Drying

The drying of the rye seed is calculated according to Nemecek et al. (2004). The rye is dried from 16 % moisture at harvest to 15 % moisture at storage. These values are based on Swiss data (Nemecek et al. 2004) because no data are available for moisture of rye in Europe.

8.8 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account) and the yield per area unit. The land occupied is always considered as “Occupation, arable, non-irrigated”, since the land is not irrigated.

Land transformation is calculated on the basis of the area required to produce 1 kg of product. The type of use before establishment of the crop is assumed to be 71% arable land and 29 meadow (sown on arable land). These percentages correspond to the proportion of arable crops and leys out of the arable surface in Germany: 11.995.000 ha arable crops (71 %), 4.968.000 ha leys (29 %), arable surface total 16.963.000 ha in 2003, taken from Statistik (2003).

In Tab. 8.13 the accounted amounts of land use are given. They are calculated with a yield of 3172 kg rye per year and ha. The occupation is calculated as permanent for 10 months per year (Nemecek et al. 2004).

Tab. 8.13 Amounts of land use for the cultivation of rye

Land use	per ha
Transformation from arable, not irrigated [m^2]	7100
Transformation from pasture and meadow [m^2]	2900
Transformation to arable, not irrigated [m^2]	10000
Occupation, arable, not irrigated [m^2a]	8333

8.9 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon balance. The carbon content of the seeds is calculated as carbon input. The biomass energy is calculated from the energy content of the rye.

Tab. 8.14 Uptake of CO_2 and biomass energy

	per ha
CO_2, biogenic [kg]	6954.3
Energy, biomass [MJ]	72564.3

8.10 Emissions to air

The emission factors according to Nemecek et al. (2004) are used for the emission of NH_3, N_2O, and NO_x to air from the mineral fertilizers:

The NH_3-N emissions are calculated with different emissions factors for the mineral fertilizers: 15 % for urea, 2 % for ammonium nitrate and calcium ammonium nitrate, and 4 % for diammonium phosphate and potassium nitrate.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that is leached as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

In Tab. 8.15 values for the emissions to air from the rye cultivation are given.

Tab. 8.15 Emissions to air from rye cultivation

Emission	Value	Unit	Source
NH3-N	3.01	[kg/ha]	calculated from the N-input
N2O	1.95	[kg/ha]	calculated from the N-input and nitrate leaching
NOx	4.08E-01	[kg/ha]	calculated from the N-input

8.11 Emissions to water

For the phosphorus emissions to water and nitrate leaching to ground water the emission factors are calculated according to the method, which is described for Switzerland in Nemecek et al. (2004).

Tab. 8.16 Emissions to water from rye cultivation

Emission	Emission factor (% of the nutrient contained in the fertilizer)	Value
Phosphorus, to surface water (kg/kg rye)	0.341	3.17E-01
Phosphorus, to ground water (kg/kg rye)	0.0752	7.00E-02
Nitrate, to ground water (kg/kg rye)	43.3	3.61E+01

8.12 Emissions to soil

The applied pesticides are calculated as emissions to soil. For pesticides, for which no elementary flows are available, comparable substances are used, which belong to the same substance class.

The differences between the inputs of heavy metals contained in the fertilizers and the seeds and the outputs through harvested products are assumed to be heavy metal emissions to soil. Some heavy metals are calculated as heavy metal uptake because the outputs are higher than the inputs.

Tab. 8.17 Emissions to soil from rye cultivation

Emission	Value (kg/kg rye)
Cd	3.05E-03
Cr	1.90E-02
Cu	-9.59E-03
Pb	7.47E-03
Ni	1.47E-02
Zn	1.17E-01
Azoxystrobin	2.24E-02
Carbendazim	5.94E-03
Cyproconazole	9.98E-03
Cyprodinil	1.18E-02
Dithianon	6.80E-03
Epoxiconazole	8.89E-03
Fenbuconazol	1.78E-03
Fenpropidin	2.83E-02
Fenpropimorph	5.64E-02
Fluquinconazole	1.55E-03
Flusilazole	6.21E-03
Kresoxim-methyl	1.06E-02
Metconazole	2.78E-03
Prochloraz	1.67E-02
Propiconazole	7.47E-03
Spiroxamine	5.10E-02
Tebuconazole	4.25E-02
Triadimenol	3.74E-03
Amidosulfuron	6.80E-04
Bentazone	1.94E-02
Chlorotoluron	1.88E-02
Cinidon-Ethyl	8.25E-04
Dichlorprop-P	3.09E-02
Diflufenican	3.00E-02
Fluroxypyr	2.04E-03
Flurtamone	1.80E-02
Glyphosate	1.98E-02
Iodosulfuron	1.03E-04
Ioxynil	3.67E-02
Isoproturon	3.43E-01
MCPA	1.24E-02
Mecoprop-P	1.61E-02
Mefenpyr	3.09E-04
Metsulfuron-methyl	1.90E-04
Pendimethalin	5.98E-02
Thifensulfuron-methyl	1.56E-04
Tribenuron	3.89E-04
Cypermethrin	3.04E-02
Deltamethrin	1.01E-04

Emission	Value (kg/kg rye)
Dimethoate	7.08E-02
Esfenvalerate	1.29E-04
Oxydemeton-methyl	7.21E-03
Parathion	5.30E-03
Pirimicarb	3.56E-03
Lamda-Cyhalothrin	1.96E-03
Chlormequat	3.90E-01
Ethephon	3.24E-01
Trinexapac-ethyl	3.13E-02

8.13 Co-products and Allocation

Rye cultivation is a multi-output process with rye grains and rye straw as allocated products. According to Nemecek et al. (2004) only 50 % of the straw is harvested, the other 50 % remain on the field. The straw can be sold. The economic value is used as allocation factor. As there are no actual market prices for rye straw in Europe available, the values are used, which are given by Nemecek et al. (2004) for Switzerland. The allocation of the uptake of CO2 and energy is calculated from the carbon content and the energy content of the allocated products. The allocation of the transports with tractor and trailer is calculated from the mass of grains and straw.

Tab. 8.18 Possible allocation parameters of the co-products from rye cultivation (Nemecek et al. 2004)

Co-products	kg/kg rye grains	Economic allocation factor
rye grains	1	90.3 %
rye straw	0.682	9.7 %

Tab. 8.19 Allocation factors for the co-products from rye cultivation

Inputs/Outputs	Rye	Straw
Inputs		
all fertilizers	90.3	9.7
all pesticides	90.3	9.7
fertilizing	90.3	9.7
ploughing	90.3	9.7
harrowing	90.3	9.7
sowing	90.3	9.7
application plant protection	90.3	9.7
combine harvesting	90.3	9.7
Chiseling	90.3	9.7
Baling		100
Loading bales		100
Tractor and trailer	59.46	40.54
Lorry 28t	90.3	9.7
Rail	90.3	9.7
Barge	90.3	9.7
grain drying	100	
Transformation from arable, not irrigated	90.3	9.7
Transformation from pasture and meadow	90.3	9.7
Transformation to arable, not irrigated	90.3	9.7
Occupation, arable, not irrigated	90.3	9.7
CO2, biogenic	57.7	42.3
Energy, biomass	58.7	41.3
Outputs		
NH3-N	90.3	9.7
N2O	90.3	9.7
NOx	90.3	9.7
Phosphorus, to surface water	90.3	9.7
Phosphorus, to ground water	90.3	9.7
Nitrate, to ground water	90.3	9.7
Heavy metals, to soil	90.3	9.7
Pesticides, to soil	90.3	9.7

1.4 Life cycle inventory of rye cultivation and data quality considerations

Tab. 8.20 shows life cycle inventory and the data quality indicators for the cultivation of rye. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 8.20 Unit process raw data for the cultivation of rye

		InputGroup	OutputGro	Name	Location	InfrastructureProcess	Unit	rye conventional	UncertaintyType	StandardDeviation95%	GeneralComment	rye grains conventional, at farm	rye straw conventional, at farm
	401												
	662			Location				RER				RER	RER
	493			InfrastructureProcess				0				0	0
	403			Unit				ha				kg	kg
allocated products		-	2	rye grains conventional, at farm	RER	0	kg	3.17E+3				100.000	-
		-	2	rye straw conventional, at farm	RER	0	kg	2.16E+3				-	100.000
resource, in air		4	-	Carbon dioxide, in air	-	-	kg	6.95E+3	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance	57.699	42.301
resource, biotic		4	-	Energy, gross calorific value, in biomass	-	-	MJ	7.26E+4	1	1.24	(4,3,1,1,1,4); calculated from the energy balance	58.707	41.293
technosphere		5	-	rye seed IP, at regional storehouse	CH	0	kg	1.40E+2	1	1.13	(1,3,1,2,1,4); Nemecek 2004	90.300	9.700
		5	-	calcium ammonium nitrate, as N, at regional storehouse	RER	0	kg	5.24E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	urea, as N, at regional storehouse	RER	0	kg	8.59E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	ammonium nitrate, as N, at regional storehouse	RER	0	kg	1.08E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	ammonium nitrate phosphate, as N, at regional storehouse	RER	0	kg	5.76E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	diammonium phosphate, as N, at regional storehouse	RER	0	kg	5.76E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	single superphosphate, as P2O5, at regional storehouse	RER	0	kg	7.76E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	triple superphosphate, as P2O5, at regional storehouse	RER	0	kg	2.33E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	1.18E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	ammonium nitrate phosphate, as P2O5, at regional storehouse	RER	0	kg	1.18E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	potassium chloride, as K2O, at regional storehouse	RER	0	kg	5.21E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	potassium nitrate, as K2O, at regional storehouse	RER	0	kg	5.64E+1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	lime, from carbonation, at regional storehouse	CH	0	kg	1.00E+3	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth	90.300	9.700
		5	-	benzimidazole-compounds, at regional storehouse	RER	0	kg	5.94E-3	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	cyclic N-compounds, at regional storehouse	RER	0	kg	1.85E-1	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	[sulfonyl]urea-compounds, at regional storehouse	RER	0	kg	1.99E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	benzo[thia]diazole-compounds, at regional storehouse	RER	0	kg	1.94E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	diphenylether-compounds, at regional storehouse	RER	0	kg	3.00E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	phenoxy-compounds, at regional storehouse	RER	0	kg	3.05E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	glyphosate, at regional storehouse	RER	0	kg	1.98E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	nitrile-compounds, at regional storehouse	RER	0	kg	3.67E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	dinitroaniline-compounds, at regional storehouse	RER	0	kg	5.98E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	pyretroid-compounds, at regional storehouse	CH	0	kg	3.23E-2	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	organophosphorus-compounds, at regional storehouse	RER	0	kg	5.30E-3	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	[thio]carbamate-compounds, at regional storehouse	RER	0	kg	3.56E-3	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	pesticide unspecified, at regional storehouse	RER	0	kg	1.31E+0	1	1.13	(1,3,1,2,1,4); Rossberg 2003	90.300	9.700
		5	-	fertilising, by broadcaster	CH	0	ha	6.95E-1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	tillage, ploughing	CH	0	ha	6.00E-1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	tillage, harrowing, by spring tine harrow	CH	0	ha	1.73E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	sowing	CH	0	ha	6.00E-1	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	application of plant protection products, by field sprayer	CH	0	ha	1.68E+0	1	1.13	(1,3,1,2,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	combine harvesting	CH	0	ha	3.85E-1	1	1.11	(1,1,1,1,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	tillage, cultivating, chiselling	CH	0	ha	6.89E-1	1	1.11	(1,1,1,1,1,4); KTBL 2004, Jungbluth 2006	90.300	9.700
		5	-	baling	CH	0	unit	7.22E+0	1	1.11	(1,1,1,1,1,4); Nemecek 2004	-	100.000
		5	-	loading bales	CH	0	unit	3.14E+1	1	1.11	(1,1,1,1,1,4); Nemecek 2004	-	100.000
		5	-	grain drying, low temperature	CH	0	kg	3.78E+1	1	1.11	(1,1,1,1,1,4); Nemecek 2004	100.000	-
		5	-	transport, lorry 28t	CH	0	tkm	6.77E+1	1	2.09	(4,5,na,na,na,na); Standard Distances	90.300	9.700
		5	-	transport, freight, rail	RER	0	tkm	6.77E+1	1	2.09	(4,5,na,na,na,na); Standard Distances	90.300	9.700
		5	-	transport, barge	RER	0	tkm	3.70E+2	1	2.09	(4,5,na,na,na,na); Standard Distances	90.300	9.700
		5	-	transport, tractor and trailer	CH	0	tkm	4.97E+1	1	2.09	(4,5,na,na,na,na); Standard Distances	59.460	40.540
resources		4	-	Transformation, from arable, non-irrigated	-	-	m2	7.10E+3	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006	90.300	9.700
resources		4	-	Transformation, from pasture and meadow	-	-	m2	2.90E+3	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006	90.300	9.700
		4	-	Transformation, to arable, non-irrigated	-	-	m2	1.00E+4	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006	90.300	9.700
		4	-	Occupation, arable, non-irrigated	-	-	m2a	8.33E+3	1	1.50	(1,1,1,1,1,1); FAOSTAT 2006	90.300	9.700
emission air, low population density		-	4	Ammonia	-	-	kg	3.01E+0	1	1.32	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
		-	4	Dinitrogen monoxide	-	-	kg	1.95E+0	1	1.58	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
		-	4	Nitrogen oxides	-	-	kg	4.08E-1	1	1.58	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
emission water, river		-	4	Phosphorus	-	-	kg	3.00E-1	1	1.58	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
emission water, ground		-	4	Phosphorus	-	-	kg	7.00E-2	1	1.58	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
		-	4	Nitrate	-	-	kg	3.61E+1	1	1.58	(4,3,1,1,1,4); Calculated with standard method	90.300	9.700
emission soil		-	4	Cadmium	-	-	kg	3.05E-3	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Chromium	-	-	kg	1.90E-2	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Copper	-	-	kg	-9.59E-3	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Nickel	-	-	kg	7.47E-3	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Lead	-	-	kg	1.47E-2	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Zinc	-	-	kg	1.17E-1	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input	90.300	9.700
		-	4	Azoxystrobin	-	-	kg	2.24E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Carbendazim	-	-	kg	5.94E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Cyproconazole	-	-	kg	9.98E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Cyprodinil	-	-	kg	1.18E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Dithianon	-	-	kg	6.80E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Epoxiconazole	-	-	kg	8.89E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Fenbuconazol	-	-	kg	1.78E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Fenpropidin	-	-	kg	2.83E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Fenpropimorph	-	-	kg	5.64E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Fluquinconazole	-	-	kg	1.55E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Flusilazole	-	-	kg	6.21E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Kresoxim-methyl	-	-	kg	1.06E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Metconazole	-	-	kg	2.78E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Prochloraz	-	-	kg	1.67E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Propiconazole	-	-	kg	7.47E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Spiroxamine	-	-	kg	5.10E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Tebuconazole	-	-	kg	4.25E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Triadimenol	-	-	kg	3.74E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Amidosulfuron	-	-	kg	6.80E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Bentazone	-	-	kg	1.94E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Chlorotoluron	-	-	kg	1.88E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Cinidon-Ethyl	-	-	kg	8.25E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Dichlorprop-P	-	-	kg	3.09E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Diflufenican	-	-	kg	3.00E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Fluroxypyr	-	-	kg	2.04E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Flurtamone	-	-	kg	1.80E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Glyphosate	-	-	kg	1.98E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Iodosulfuron	-	-	kg	1.03E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Ioxynil	-	-	kg	3.67E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Isoproturon	-	-	kg	3.43E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	MCPA	-	-	kg	1.24E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Mecoprop-P	-	-	kg	1.61E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Mefenpyr	-	-	kg	3.09E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Metsulfuron-methyl	-	-	kg	1.90E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Pendimethalin	-	-	kg	5.98E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Thifensulfuron-methyl	-	-	kg	1.56E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Tribenuron	-	-	kg	3.89E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Cypermethrin	-	-	kg	3.04E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Deltamethrin	-	-	kg	1.01E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Dimethoate	-	-	kg	7.08E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Esfenvalerate	-	-	kg	1.29E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Oxydemeton-methyl	-	-	kg	7.21E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Parathion	-	-	kg	5.30E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Pirimicarb	-	-	kg	3.56E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Lamda-Cyhalothrin	-	-	kg	1.96E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Chlormequat	-	-	kg	3.90E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Ethephon	-	-	kg	3.24E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700
		-	4	Trinexapac-ethyl	-	-	kg	3.13E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application	90.300	9.700

8.14 Cumulative Results and Interpretation

1.4.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

1.4.2 Cultivation of rye

Tab. 8.21 shows selected LCI results and the cumulative energy demand for the cultivation of rye and a comparison of these results with the ecoinvent dataset rye grains, IP, at farm, CH. The differences are due to the significant lower yield in the European Union (3172 kg grains per ha)) compared to Switzerland (7560 kg per ha)., which is caused by the dryer climate in East-Germany and Poland, which are very important regions in the European rye production.

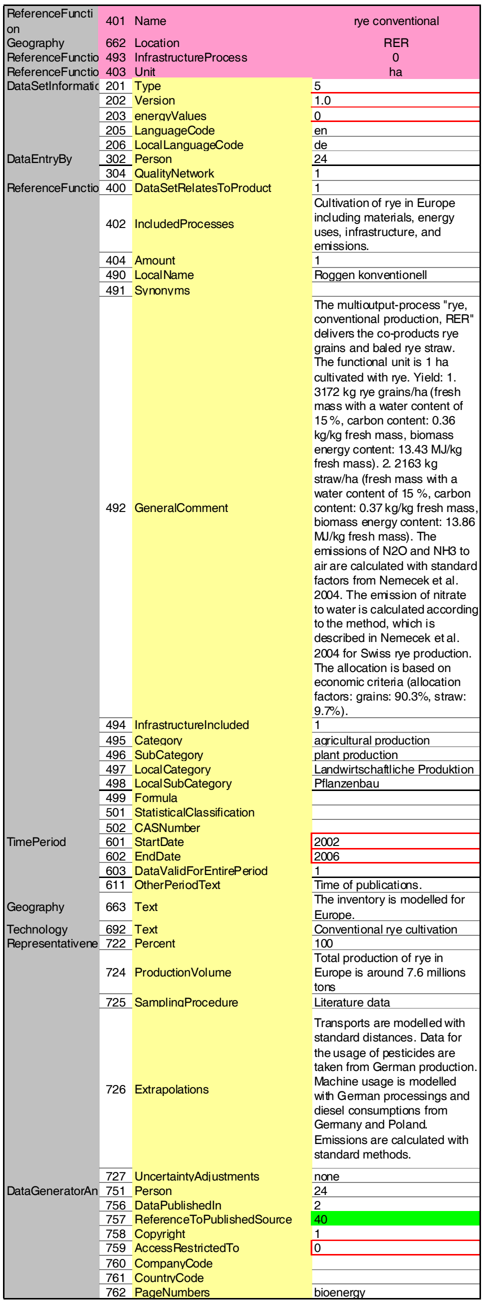
Tab. 8.21 Selected LCI results and the cumulative energy demand for the cultivation of rye

		Name		rye grains conventional, at farm	rye straw conventional, at farm	rye grains IP, at farm	rye straw IP, at farm
c		Location		RER	RER	CH	CH
		Unit	Unit	kg	kg	kg	kg
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.8	1.2	2.0	0.5
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.4	0.1	0.2	0.0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.0	0.1	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	14.1	14.0	15.5	17.5
LCI results							
resource	Land occupation	total	m2a	2.4E+0	3.9E-1	1.1E+0	1.7E-1
air	Carbon dioxide, fossil	total	kg	2.2E-1	6.1E-2	1.2E-1	2.8E-2
air	NMVOC	total	kg	2.5E-4	9.3E-5	1.5E-4	4.6E-5
air	Nitrogen oxides	total	kg	1.6E-3	4.8E-4	9.9E-4	2.4E-4
air	Sulphur dioxide	total	kg	7.3E-4	1.9E-4	3.6E-4	8.9E-5
air	Particulates, < 2.5 um	total	kg	1.6E-4	4.9E-5	1.0E-4	2.5E-5
air	Dinitrogen monoxide	total	kg	9.2E-4	1.5E-4	5.4E-4	8.7E-5
air	Methane, fossil	total	kg	3.9E-4	1.1E-4	1.9E-4	4.8E-5
water	BOD	total	kg	6.0E-4	1.6E-4	3.5E-4	7.9E-5
soil	Cadmium	total	kg	8.7E-7	1.4E-7	1.2E-7	6.9E-7
water	Phosphorus	total	kg	2.0E-5	3.1E-6	4.0E-9	8.2E-10
water	Nitrate	total	kg	1.1E-2	1.7E-3	1.5E-2	2.4E-3
Further LCI results							
air	Carbon dioxide, biogenic	total	kg	-1.3E+0	-1.4E+0	-1.3E+0	-1.4E+0
air	Carbon dioxide, land transformation	low population density	kg	4.0E-5	6.4E-6	1.9E-5	3.1E-6
air	Methane, biogenic	total	kg	1.2E-6	2.5E-7	5.8E-7	1.1E-7
air	Carbon monoxide, biogenic	total	kg	1.5E-5	6.4E-6	1.1E-5	1.9E-6

8.15 Conclusions

The life cycle inventory for the rye cultivation in Europe is determined largely by the different yields in the European countries. For further work more information about different machine usages should be included. The emissions of N_2O, NOx and NH_3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information



ReferenceFunction	401	Name	rye conventional
Geography	662	Location	RER
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	ha
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of rye in Europe including materials, energy uses, infrastructure, and emissions.
	404	Amount	1
	490	LocalName	Roggen konventionell
	491	Synonyms	
	492	GeneralComment	The multioutput-process "rye, conventional production, RER" delivers the co-products rye grains and baled rye straw. The functional unit is 1 ha cultivated with rye. Yield: 1. 3172 kg rye grains/ha (fresh mass with a water content of 15 %, carbon content: 0.36 kg/kg fresh mass, biomass energy content: 13.43 MJ/kg fresh mass). 2. 2163 kg straw/ha (fresh mass with a water content of 15 %, carbon content: 0.37 kg/kg fresh mass, biomass energy content: 13.86 MJ/kg fresh mass). The emissions of N2O and NH3 to air are calculated with standard factors from Nemecek et al. 2004. The emission of nitrate to water is calculated according to the method, which is described in Nemecek et al. 2004 for Swiss rye production. The allocation is based on economic criteria (allocation factors: grains: 90.3%, straw: 9.7%).
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2002
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled for Europe.
Technology	692	Text	Conventional rye cultivation
Representativene	722	Percent	100
	724	ProductionVolume	Total production of rye in Europe is around 7.6 millions tons
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances. Data for the usage of pesticides are taken from German production. Machine usage is modelled with German processings and diesel consumptions from Germany and Poland. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	bioenergy

References

FAOSTAT 2006	Faostat Database Query: Rye Production. Retrieved 16. May 2006, from http://faostat.fao.org/faostat/
Frischknecht et al. 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.

Jungbluth, Niels 2006	Life cycle inventory of wheat straw production in Europe. Personal communication 2006
Kaltschmidt et al. 1997	Kaltschmitt, M. & Reinhardt, G. (1997): Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung. Verlag Vieweg, Braunschweig/Wiesbaden.
KTBL 2004	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.: Betriebsplanung Landwirtschaft 2004/2005 – Daten für die Betriebsplanung in der Landwirtschaft. 20. Auflage. Darmstadt
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Roßberg et al. 2002	Roßberg, D./Gutsche, V./Enzian, S./Wick, M. (2002): Neptun 2000 - Erhebung von Daten zum tatsächlichen Einsatz chemischer Pflanzenschutzmittel im Ackerbau Deutschlands. Berichte aus der Biologischen Bundesanstalt für Land- und Forstwirtschaft Heft 98
Statistik 2003	Statistisches Bundesamt (Hrsg.) (2003): Statistisches Jahrbuch 2003. Statistisches Bundesamt, Wiesbaden 2003

9 Soybean

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Review: Niels Jungbluth, ESU-services, Uster
Last changes: 2006

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9.1 Introduction

Soybean (*Glycine max* L.) is a tropical crop of the family *Fabaceae*. It is an important crop in the world and is cultivated for its oil and protein.

The world production of soybeans is around 210 million tons per year (FAOSTAT 2006). The leading producing countries are the USA (39.4 % of the world production), Brazil (23.9 %), and Argentina (18.2 %).

For this inventory the functional unit is 1 kg of soybeans (fresh matter). The properties of soybeans are given in Tab. 9.1.

Tab. 9.1 Properties of soybeans (Nemecek et al. 2004)

Property	Value	Unit
Water	0.11	kg/kg soybeans fresh matter
C content	0.388	kg/kg soybeans fresh matter
HHV	20.45	MJ/kg soybeans fresh matter
Cd	0.053	mg/kg soybeans fresh matter
Cr	0.463	mg/kg soybeans fresh matter
Cu	13.4	mg/kg soybeans fresh matter
Ni	4.73	mg/kg soybeans fresh matter
Pb	0.07	mg/kg soybeans fresh matter
Zn	42.45	mg/kg soybeans fresh matter

9.2 System Characterisation

This report corresponds to the dataset for the production of 1 kg soy bean, at farm.

As the USA and Brazil are the countries with largest amounts of produced soybeans, the following processes are modelled:

- soybean, at farm, US
- soybean, at farm, BR

All data in the present report are referred to 1 kg soybean fresh matter. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of the raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

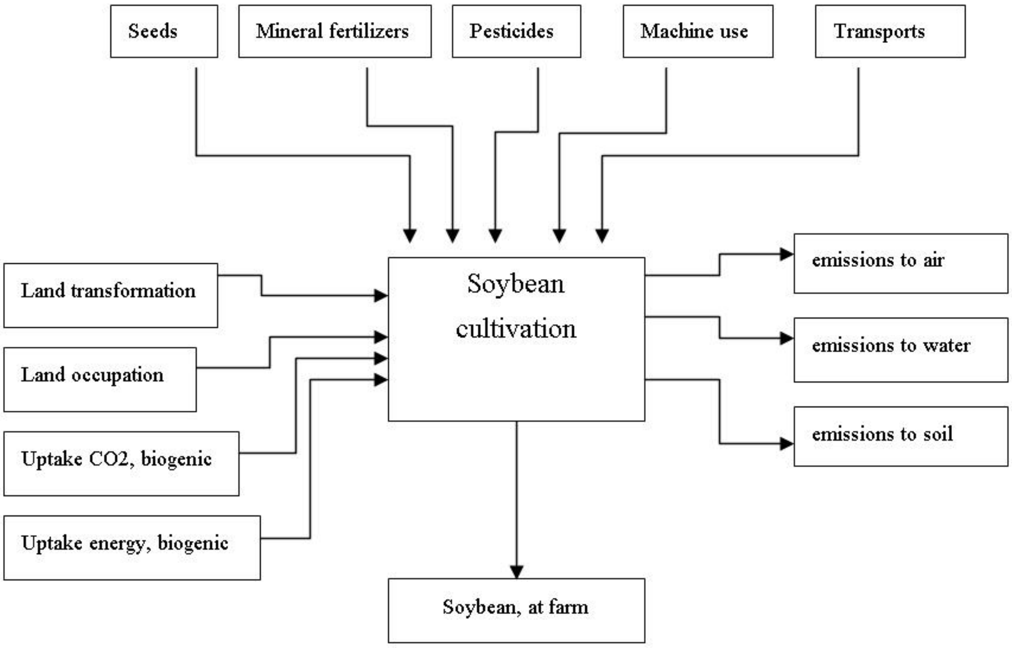

Fig. 9.1 **Process flow chart for the cultivation of soybeans**

9.3 Yields

In Tab. 9.2 data for the soybean cultivation in USA and Brazil are given. The data are based on international statistics of FAOSTAT (2006). The yield, which is used in this study, is based on an average over the last five years to adjust annual deviations.

Tab. 9.2 **Soybean cultivation in the USA and Brazil (FAOSTAT 2006)**

Soy bean production	USA	Brazil
Area (1000 ha)	28842	22895
Yield 2001 (kg/ha)	2664	2795
Yield 2002 (kg/ha)	2553	2613
Yield 2003 (kg/ha)	2277	2808
Yield 2004 (kg/ha)	2840	2314
Yield 2005 (kg/ha)	2872	2192
Average yield over 5 years (kg/ha)	2641	2544

9.4 Raw materials and auxiliaries

1.4.3 Fertilizers

In Tab. 9.3 quantities for the fertilizer use in the soybean cultivation are given. As soybean is a leguminous, which is able to fix atmospheric nitrogen because of its symbiotic relationship with rhizobioa bacteria, the amount of used N-fertilizer is very low compared to other crops. The data for the USA are based on statistics by NASS (2005). The data for Brazil are based on the Brazilian Agricultural Report (FNP 2000, quotated in Ostermayer 2002).

Tab. 9.3 Fertilizer use in the soybean cultivation

Fertilizer	USA (NASS 2005)	Brazil (Ostermayer 2002)
N [kg/ha/y]	5	-
P_2O_5 [kg/ha/y]	16.16	30
K_2O [kg/ha/y]	24.64	30

Tab. 9.4 Fertilizer use by product (IFA 2006)

Nutrient	Product	% in the USA	% in Brazil
		IFA 2006	FAO 2004
N	Ammonium sulphate		-
	Urea	21	-
	Ammonium nitrate	29	-
	DAP		-
	NPK		-
	Anhydrous ammonia	50	-
P2O5	DAP	100	45
	SSP		29
	TSP		16
	Phosphate rock		5
	NPK		5
K2O	Potassium chloride	100	100

Tab. 9.5 Use of fertilizers in the cultivation of soybean

Product	USA	Brazil
	kg kg-1 soybean	kg kg-1 soybean
ammonium sulphate as N		5.6604E-04
urea as N	3.9758E-04	1.6981E-03
ammonium nitrate as N	5.4903E-04	5.6604E-04
Ammonia	9.4661E-04	
diammonium phosphate as N		4.9528E-04
potassium nitrate as N		2.1226E-04
diammonium phosphate as P2O5	6.1204E-03	1.1675E-02
single superphosphate as P2O5		7.5236E-03
triple superphosphate as P2O5		4.1509E-03
phosphate rock as P2O5		1.2972E-03
ammonium nitrate phosphate as P2O5		1.2972E-03
potassium chloride as K2O	9.3309E-03	2.4371E-02
lime	8.35E-03	
Total fertilizers	**2.569E-02**	**5.385E-02**

1.4.4 Pesticides and Biological Control

USDA (2004a) reports amounts of pesticides use in the soybean cultivation in the USA. The data for the soybean cultivation in Brazil are taken from Cederberg 2001.

Tab. 9.6 Pesticides use in the soybean cultivation (USDA 2004a, Cederberg 2001)

Pesticide	USA [kg/ha/y]	Brazil [kg/ha/y]	Used dataset
2,4-D	1.1433E-02	7.5E-01	phenoxy-compounds
Acetic acid (2,4-D)	5.2680E-03		phenoxy-compounds
Chlorimuron-ethyl	1.5692E-03		sulfonyl-urea-compounds
Clethodim	2.2417E-03		benzimidazole-compounds
Cloransulam-methyl	6.7251E-04		thio-carbamate-compounds
Dibensulfuron		5.6E-03	sulfonyl-urea-compounds
Endosulfan		6.6E-02	pesticides, unspecified
Fenoxaprop	1.3450E-03		phenoxy -compounds
Fluazifop-P-butyl	4.4830E-04		diphenyether-compounds
Flumioxazin	7.8460E-04		triazine-compounds
Fomesafen	5.1559E-03		dinitroaniline -compounds
Glyphosate	2.0399E-02	5.4E-01	organophosphorus-compounds
Glyphosate iso. Salt	1.0532		organophosphorus-compounds
Imazamox	6.7251E-04		diphenyether -compounds
Imazethapyr	1.6813E-03		phenoxy-compounds
Metribuzin	5.3801E-03		triazine-compounds
Monocrotofos		1.12E-01	organophosphorus-compounds
Pendimethalin	3.9006E-02		dinitroaniline-compounds
S-Metolachlor	1.4347E-02		acetamide-anilide -compounds
Sulfentrazone	8.0701E-03		benzo(thia)diazole-compounds
Sulfosate	3.3401E-02		organophosphorus-compounds
Trifluralin	4.7076E-02		dinitroaniline -compounds
Chlorpyrofos	5.0438E-03		organophosphorus -compounds
Lambda-cyhalothrin	2.2417E-04		pyretroid-compounds

Tab. 9.7 Use of pesticides in the cultivation of soybean in this study

Product	kg kg^{-1} soybean (USA)	kg kg^{-1} soybean (Brazil)
phenoxy-compounds	7.46951E-06	2.94811E-04
sulfonyl-urea-compounds	5.94165E-07	2.20126E-06
benzimidazole-compounds	8.48807E-07	
thio-carbamate-compounds	2.54642E-07	
diphenyether-compounds	4.24404E-07	
triazine-compounds	2.33422E-06	
dinitroaniline -compounds	3.45465E-05	
organophosphorus-compounds	4.21051E-04	2.56289E-04
acetamide-anilide -compounds	5.43237E-06	
benzo(thia)diazole-compounds	3.05571E-06	
pyretroid-compounds	8.48807E-08	
pesticides, unspecified		2.59434E-05
Total pesticides	**4.76E-04**	**5.79E-04**

1.4.5 Seed

The value of 70 kg seeds per ha is taken from Ostermayer (2002). According to Nemecek et al. (2004) the use of the seeds is calculated with the dataset “pea seed IP, at regional storage, CH”.

9.5 Energy and machine usage

Cultivation

NREL (2006), Ostermayer (2002), and Cederberg (2001) report data for the diesel use in the cultivation of soybeans in the USA and Brazil. Ostermayer (2002) reports diesel consumptions for several field works in the USA. The proportions of these field works are used to calculate machine usages with the diesel consumption values for these field works from Nemecek et al. (2004).

Tab. 9.8 Machine use and diesel consumption in the soybean cultivation in the USA

Diesel consumption	[l/ha/y]
NREL (2006)	55.42
Ostermayer (2002)	50.8 - 51.7
This study	55.42

Tab. 9.9 Machine use and diesel consumption in the soybean cultivation in Brazil

Diesel consumption	[l/ha/y]
Cederberg (2001)	60
Ostermayer (2002)	70
This study (average)	65

Tab. 9.10 Machine use in the soybean cultivation

Process	% of the total diesel consumption in the soybean cultivation, according to Ostermayer (2002)	Machine use USA	Machine use Brazil
		[ha/kg soybean]	[ha/kg soybean]
ploughing	13.8	9.30E-05	1.09E-04
harrowing	7.5	2.97E-04	3.49E-04
application plant protection	2.6	2.55E-04	2.99E-04
fertilizing	1.6	5.35E-05	6.28E-05
sowing	4.4	2.04E-04	2.39E-04
combine harvesting	20.1	1.06E-04	1.25E-04

9.6 Transportation

For the transports of the seeds, the fertilizers, the pesticides, and the soybeans to farm in Brazil the standard distances, which are given in Nemecek et al. (2004), are used. For the transports of the inputs in the USA the values are used, which are given by NREL (2006). The transports of the soybeans from the field to the farm are calculated with the standard distances, which are given in Nemecek et al. (2004).

Tab. 9.11 Transports distances in the soybean cultivation in Brazil

Material	Tractor and trailer [km]	Lorry 28t [km]	Rail [km]	Barge [km]
Seeds	15			
N-fertilizers		100	100	900
P-fertilizers		100	100	400
K-fertilizers		100	100	100
Pesticides	15			
soybeans	15			

Tab. 9.12 Transports in the soybean cultivation in the USA

Material	Tractor [km]	Rail [tkm]	Lorry 32 t [kg diesel]
Total inputs		4.63E-02	1.014E-03
soybeans	15		
fertilizers	15		
seeds	15		
pesticides	15		

The transports with lorry are converted with the diesel consumption of lorry transports from Spielmann (2004).

Tab. 9.13 Transport service requirements of raw materials and auxiliaries per kg soybean

Material	USA	Brazil
lorry 28t [tkm]		5.39E-03
lorry 32t [tkm]	2.23E-02	5.39E-03
rail [tkm]	4.63E-03	5.39E-03
barge [tkm]		1.60E-02
tractor and trailer [tkm]	1.59E-02	1.57

9.7 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account) and the yield per area unit. The land occupied was always considered as “Occupation, arable”.

Land transformation was calculated on the basis of the area required to produce 1 kg of soybeans.

In the USA the type of use before establishment of the crop was assumed to be arable land.

In Brazil the type of use before establishment of the crop was assumed to be arable land, transformation from tropical rain forest, or transformation from shrub land (Cerrado ecosystems). The increasing of the area cultivated with soybeans is one reason for the devastation of the tropical rainforests in Brazil.

The area, which has been transformed from tropical rainforests, can be cultivated for only a few years (Mattson et al. 2000). Altieri et al (2006) reports a cultivation time of two years, then the area is converted to pasture.

As the area, which is used for soybean cultivation in Brazil, has increased by 1'700'000 ha per year over the last 5 years (USDA 2004b), 3.2 % of the used land is calculated as “transformed from tropical rain forest" and 5.2 % of the used land is calculated as "transformed from shrub land" (calculated with the land use in the different Brazilian states, taken from Bickel 2003).

In Tab. 9.15 the accounted amounts of land use are given. They are calculated with a yield of 2641 kg soybeans per year and ha in the USA and 2544 kg soybeans per ha and 0.5 year in Brazil. The occupation is calculated as permanent for 12 months per year in the USA and for 6 months in Brazil,

Tab. 9.14 Land use for the cultivation of soybeans in Brazil per year (calculated with data from USDA 2004b, Bickel 2003)

Land use	Brazil total	South Brazil	North Brazil
total area in 2004 [Million ha]	23.5	11.0	12.5
total area in 2003 [Million ha] (Total are in 2004 – rise per year)	21.8	10.6	11.2
Rise of the total area [Million ha] In the last 5 years: 6.1. Million ha in North Brazil 2.3 Million ha in South Brazil	1.7	0.5	1.2
% of total cultivated area in Brazil		47 %	53 %
Transformation from arable area [Million ha]	21.5	10.6	10.9
Transformation to pasture [Million ha] (rise per year * 49% / 2 years)	0.299	0	0.299
New area [% of the total cultivated area] (rise of the total area + transformation to pasture)	8.4 %	4.2 %	12.2 %
From rainforest [% of the new cultivated area]		0 %	49 %
From Cerrado Ecosystems [% of the new cultivated area]		100 %	51 %
Transformation from tropical rainforest [Million ha]	0.74	0	0.74
Transformation from shrub land [Million ha]	1.23	0.46	0.77
Transformation from arable area [Million ha]	21.52	10.58	10.94
Transformation from tropical rainforest [% of the total cultivated area]	3.2 %	0 %	5.98 %
Transformation from shrub land [% of the total cultivated area]	5.2 %	4.2 %	6.2 %
Transformation from arable area [% of the total cultivated area]	91.6 %	95.8 %	87.8 %

Tab. 9.15 Amounts of land use for the cultivation of soybeans

Land use	USA	Brazil
Transformation from arable [m2 per kg soybean]	3.79	3.77
Transformation from tropical rainforest [m2 per kg soybean]	-	6.2E-02
Transformation from shrub land, sclerophyllous [m2 per kg soybean]	-	1.0E-01
Transformation to arable [m2 per kg soybean]	3.79	3.93
Occupation, arable, not irrigated [m2a per kg soybean]	3.79	1.97

9.8 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon balance. The carbon content of the seeds is calculated as carbon input. The uptake of CO_2 in the US cultivation differs from the Brazilian cultivation because of the different seed input. The biomass energy is calculated from the energy content of soybeans.

Tab. 9.16 Uptake of CO_2 and biomass energy

	USA	Brazil
CO_2, biogenic [kg/kg soybeans]	1.370	1.368
Energy, biomass [MJ/kg soybeans]	20.45	20.45

1.5 Carbon loss from soil after deforestation

From the soil 12.3 tons of carbon per ha is lost due to the conversion from rainforest to agricultural area in Brazil (Fearnside 2000). The lost carbon from soil is calculated as consumption of the resource "carbon, in organic matter, in soil".

This leads to an emission of 184 tons of CO2 per ha deforestated rainforest. All CO2 emissions from the deforestation are allocated to the use as agricultural land.

Tab. 9.17 Consumption of carbon in soil

Resource	per ha rainforest	per kg soybean
Carbon, in organic matter, in soil (kg)	12300	7.66E-02

9.9 Emissions to air

For the emission of NH_3, N_2O, and NO_x to air from the mineral fertilizers the emission factors according to Nemecek et al. (2004) are used:

The NH_3-N emissions are calculated with the emission factors for the several mineral fertilizers which are described in Nemecek et al. (2004).

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that is leached as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

NH_3, N_2O, and NO_x are also emitted from the crop residue. The emissions are calculated with a value of 70 kg N per ha factors fixed by the rhizobia bacteria (Ostermayer 2002) and the following emission factors (according to Ostermayer 2002):

The NH_3-N emissions are calculated with a emission factor of 3.29 % of the fixed N.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the fixed N.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

The emission of CO2 caused by the carbon loss from soil after deforestation of the tropical rainforest in Brazil is calculated as “CO2, land transformation”.

In Tab. 9.18 values for the emissions to air from soybean cultivation are given.

Tab. 9.18 Emissions to air from soybean cultivation

Emission	USA	Brazil	Source
NH3-N [kg/kg soybean]	9.43E-04	9,05E-04	calculated from the N-input
N2O [kg/kg soybean]	3.55E-04	9,8E-04	calculated from the N-input and nitrate leaching
NOx [kg/kg soybean]	7.45E-05	2.06E-04	calculated from the N-input
CO2, land transformation [kg/kg soybean]	-	2.81E-01	from deforestation

9.10 Emissions to water

For the phosphorus emissions to water the emission factors are calculated according to the method, which is described for the soybean cultivation in Switzerland in Nemecek et al. (2004). For the calculation the same factors are used, which are described in Nemecek et al. (2004) for Switzerland.

The nitrate leaching is calculated with an emission factor of 30 % of the N-input (fertilizers and N fixation) (according to Ostermayer 2002). The N-fixation is calculated with a value of 70 kg N per ha (Ostermayer 2002)

Tab. 9.19 Emissions to water from soybean cultivation

Emission	USA	Brazil
Phosphorus, to surface water [kg/kg soybean]	3.01E-04	3.15E-04
Phosphorus, to ground water [kg/kg soybean]	2.65E-05	2.75E-05
Nitrate, to ground water [kg/kg soybean]	3.77E-02	3.66E-02

9.11 Emissions to soil

The applied pesticides are calculated as emissions to soil. Acetic acid (2,4-D) is calculated as 2,4-D, glyphosate iso. salt is calculated as glyphosate.

The differences between the inputs of heavy metals contained in the fertilizers and the seeds and the outputs through harvested products are assumed to be heavy metal emissions to soil. Some heavy metals are calculated as heavy metal uptake because the outputs are higher than the inputs.

Tab. 9.20 Emissions to soil from soybean cultivation

Emission	USA (kg/kg soybean)	Brazil (kg/kg soybean)
Cd	-4.95E-08	8.83E-07
Cr	-3.19E-07	5.57E-06
Cu	-1.28E-05	-1.10E-05
Ni	-4.24E-06	-2.53E-06
Pb	6.36E-08	4.68E-06
Zn	-3.92E-05	-2.85E-05
2,4-D	6.32E-06	2.95E-04
Chlorimuron-ethyl	5.94E-07	
Clethodim	8.49E-07	
Cloransulam-methyl	2.55E-07	
Fenoxaprop	5.09E-07	
Fluazifop-P-butyl	1.70E-07	
Flumioxazin	2.97E-07	
Fomesafen	1.95E-06	
Glyphosate	4.06E-04	2.12E-04
Imazamox	2.55E-07	
Imazethapyr	6.37E-07	
Metribuzin	2.04E-06	
Pendimethalin	1.48E-05	
Metolachlor	5.43E-06	
Sulfentrazone	3.06E-06	
Sulfosate	1.26E-05	
Trifluralin	1.78E-05	
Chlorpyrofos	1.91E-06	
Lambda-cyhalothrin	8.49E-08	2.2E-06
Monocrotofos		4.40E-05
Dibensulfuron		2.20E-06
Endosulfan		2.59E-05
Total pesticides	4.76E-04	5.79E-04

9.12 Life cycle inventory of soybean cultivation and data quality considerations

Tab. 9.21 shows the life cycle inventory and the data quality indicators for the cultivation of soybean in the USA. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 9.21 Unit process raw data for the cultivation of soybeans in the USA

401	InputGroup	OutputGroup	Name	Location	InfrastructureProcess	Unit	soybeans, at farm	Uncertainty Type	StandardDeviation95%	GeneralComment
662			Location				US			
493			InfrastructureProcess				0			
403			Unit				kg			
	-	0	soybeans, at farm	US	0	kg	1.00E+0			
resource, in air	4	-	Carbon dioxide, in air	-	-	kg	1.37E+0	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	-	MJ	2.05E+1	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
technosphere	5	-	urea, as N, at regional storehouse	RER	0	kg	3.98E-4	1	1.06	(1,2,1,3,1,1); IFA 2006; NASS 2005
	5	-	ammonium nitrate, as N, at regional storehouse	RER	0	kg	5.49E-4	1	1.06	(1,2,1,3,1,1); IFA 2006; NASS 2005
	5	-	ammonia, liquid, at regional storehouse	RER	0	kg	9.47E-4	1	1.06	(1,2,1,3,1,1); IFA 2006; NASS 2005
	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	6.12E-3	1	1.06	(1,2,1,3,1,1); IFA 2006; NASS 2005
	5	-	potassium chloride, as K2O, at regional storehouse	RER	0	kg	9.33E-3	1	1.06	(1,2,1,3,1,1); IFA 2006; NASS 2005
	5	-	lime, from carbonation, at regional storehouse	CH	0	kg	8.35E-3	1	1.06	(1,2,1,3,1,1); NREL 2006
	5	-	phenoxy-compounds, at regional storehouse	RER	0	kg	7.47E-6	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	[sulfonyl]urea-compounds, at regional storehouse	RER	0	kg	5.94E-7	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	benzimidazole-compounds, at regional storehouse	RER	0	kg	8.49E-7	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	[thio]carbamate-compounds, at regional storehouse	RER	0	kg	2.55E-7	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	diphenylether-compounds, at regional storehouse	RER	0	kg	4.24E-7	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	triazine-compounds, at regional storehouse	RER	0	kg	2.33E-6	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	dinitroaniline-compounds, at regional storehouse	RER	0	kg	3.45E-5	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	organophosphorus-compounds, at regional storehouse	RER	0	kg	4.21E-4	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	acetamide-anillide-compounds, at regional storehouse	RER	0	kg	5.43E-6	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	benzo[thia]diazole-compounds, at regional storehouse	RER	0	kg	3.06E-6	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	pyretroid-compounds, at regional storehouse	CH	0	kg	8.49E-8	1	1.06	(1,2,1,3,1,1); USDA 2004
	5	-	tillage, ploughing	CH	0	ha	9.30E-5	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	tillage, harrowing, by spring tine harrow	CH	0	ha	2.97E-4	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	application of plant protection products, by field sprayer	CH	0	ha	2.55E-4	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	fertilising, by broadcaster	CH	0	ha	5.35E-5	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	sowing	CH	0	ha	2.04E-4	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	combine harvesting	CH	0	ha	1.06E-4	1	1.08	(2,2,1,3,1,1); NREL 2006; Nemecek 2004
	5	-	pea seed IP, at regional storehouse	CH	0	kg	4.17E-2	1	1.31	(2,3,1,3,3,5); Nemecek 2004
	5	-	transport, lorry 32t	RER	0	tkm	2.23E-2	1	2.00	(1,2,1,3,1,1); NREL 2006; Spielmann 2004
	5	-	transport, freight, rail	RER	0	tkm	4.63E-2	1	2.00	(1,2,1,3,1,1); NREL 2006
	5	-	transport, tractor and trailer	CH	0	tkm	1.50E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
resources	4	-	Transformation, from arable, non-irrigated	-	-	m2	3.79E+0	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006
	4	-	Transformation, to arable, non-irrigated	-	-	m2	3.79E+0	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006
	4	-	Occupation, arable, non-irrigated	-	-	m2a	3.79E+0	1	1.50	(1,1,1,1,1,1); FAOSTAT 2006; Nemecek 2004
emission air, low population density	-	4	Ammonia	-	-	kg	9.43E-4	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	-	kg	3.55E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	-	kg	7.45E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, river	-	4	Phosphorus	-	-	kg	3.01E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	-	kg	2.65E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrate	-	-	kg	3.77E-2	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission agricultural soil	-	4	Cadmium	-	-	kg	-4.95E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Chromium	-	-	kg	-3.19E-7	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Copper	-	-	kg	-1.28E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Nickel	-	-	kg	-4.24E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Lead	-	-	kg	6.36E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Zinc	-	-	kg	-3.92E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	2,4-D	-	-	kg	6.32E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Chlorimuron-ethyl	-	-	kg	5.94E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Clethodim	-	-	kg	8.49E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Cloransulam-methyl	-	-	kg	2.55E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Fenoxaprop	-	-	kg	5.09E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Fluazifop-P-butyl	-	-	kg	1.70E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Flumioxazin	-	-	kg	2.97E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Fomesafen	-	-	kg	1.95E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Glyphosate	-	-	kg	4.06E-4	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Imazamox	-	-	kg	2.55E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Imazethapyr	-	-	kg	6.37E-7	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Metribuzin	-	-	kg	2.04E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Pendimethalin	-	-	kg	1.48E-5	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Metolachlor	-	-	kg	5.43E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Sulfentrazone	-	-	kg	3.06E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Sulfosate	-	-	kg	1.26E-5	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Trifluralin	-	-	kg	1.78E-5	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Chlorpyrifos	-	-	kg	1.91E-6	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application
	-	4	Lamda-Cyhalothrin	-	-	kg	8.49E-8	1	1.30	(4,3,1,1,1,1); Calculated from the pesticide application

Tab. 9.22 shows the life cycle inventory and the data quality indicators for the cultivation of soybean in Brazil. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 9.22 Unit process raw data for the cultivation of soybeans in Brazil

401	InputGroup	OutputGroup	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	soybeans, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location						BR			
493			InfrastructureProcess						0			
403			Unit						kg			
	-	0	soybeans, at farm	BR	-	-	0	kg	1.00E+0			
resource, in air	4	-	Carbon dioxide, in air	-	resour	in air	-	kg	1.37E+0	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	resour	biotic	-	MJ	2.05E+1	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
	4	-	Wood, primary forest, standing	-	resour	biotic	-	m3	2.15E+2	1	1.24	(4,3,1,1,1,4); calculated from the deforestation
resource, in ground	4	-	Carbon, in organic matter, in soil	-	resour	in ground	-	kg	7.66E-2	1	1.24	(4,3,1,1,1,4); calculated from the deforestation
technosphere	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	5.31E-3	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	single superphosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	3.42E-3	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	triple superphosphate, as P2O5, at regional storehouse	RER	-	-	0	kg	1.89E-3	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	phosphate rock, as P2O5, beneficiated, dry, at plant	MA	-	-	0	kg	5.90E-4	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	ammonium nitrate phosphate, as N, at regional storehouse	RER	-	-	0	kg	5.90E-4	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	potassium chloride, as K2O, at regional storehouse	RER	-	-	0	kg	1.18E-2	1	1.16	(3,3,1,1,1,4); FAO 2004
	5	-	phenoxy-compounds, at regional storehouse	RER	-	-	0	kg	2.95E-4	1	1.33	(3,3,4,1,1,5); Cederberg 2001
	5	-	[sulfonyl]urea-compounds, at regional storehouse	RER	-	-	0	kg	2.56E-4	1	1.33	(3,3,4,1,1,5); Cederberg 2001
	5	-	organophosphorus-compounds, at regional storehouse	RER	-	-	0	kg	2.20E-6	1	1.33	(3,3,4,1,1,5); Cederberg 2001
	5	-	pesticide unspecified, at regional storehouse	RER	-	-	0	kg	2.59E-5	1	1.33	(3,3,4,1,1,5); Cederberg 2001
	5	-	tillage, ploughing	CH	-	-	0	ha	1.09E-4	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2007
	5	-	tillage, harrowing, by spring tine harrow	CH	-	-	0	ha	3.49E-4	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2007
	5	-	application of plant protection products, by field sprayer	CH	-	-	0	ha	2.99E-4	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2007
	5	-	fertilising, by broadcaster	CH	-	-	0	ha	6.28E-5	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2007
	5	-	sowing	CH	-	-	0	ha	2.39E-4	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2006
	5	-	combine harvesting	CH	-	-	0	ha	1.25E-4	1	1.27	(3,3,3,3,1,5); Cederberg 2001; Ostermayer 2007
	5	-	pea seed IP, at regional storehouse	CH	-	-	0	kg	4.17E-2	1	1.68	(4,5,na,na,4,5); Nemecek 2004
	5	-	transport, lorry 28t	CH	-	-	0	tkm	2.36E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, freight, rail	RER	-	-	0	tkm	2.36E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, barge	RER	-	-	0	tkm	5.90E-3	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, tractor and trailer	CH	-	-	0	tkm	1.57E-2	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	provision, stubbed land	BR	-	-	0	m2	6.22E-2	1	1.30	(4,5,na,na,na,na); FAOSTAT 2006; USDA 2004
resources	4	-	Transformation, from arable, non-irrigated	-	resour	land	-	m2	3.77E+0	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006; USDA 2004
	4	-	Transformation, from shrub land, sclerophyllous	-	resour	land	-	m2	1.03E-1	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006; USDA 2004
	4	-	Transformation, to arable, non-irrigated	-	resour	land	-	m2	3.93E+0	1	2.00	(1,1,1,1,1,1); FAOSTAT 2006
	4	-	Occupation, arable, non-irrigated	-	resour	land	-	m2a	1.97E+0	1	1.50	(1,1,1,3,1,1); FAOSTAT 2006; Nemecek 2004
emission air, low population density	-	4	Ammonia	-	air	low population density	-	kg	9.05E-4	1	1.32	(4,3,1,3,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	air	low population density	-	kg	9.80E-4	1	1.58	(4,3,1,3,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	air	low population density	-	kg	2.06E-4	1	1.58	(4,3,1,3,1,4); Calculated with standard method
	-	4	Carbon dioxide, land transformation	-	air	low population density	-	kg	2.81E-1	1	1.49	(4,3,1,3,1,4); Carbon loss from soil after deforestation
emission water, river	-	4	Phosphorus	-	water	river	-	kg	3.15E-4	1	1.58	(4,3,1,3,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	water	ground-	-	kg	2.75E-5	1	1.58	(4,3,1,3,1,4); Calculated with standard method
	-	4	Nitrate	-	water	ground-	-	kg	3.66E-2	1	1.58	(4,3,1,3,1,4); Ostermayer 2002
emission agricultural soil	-	4	Cadmium	-	soil	agricultural	-	kg	3.73E-7	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Chromium	-	soil	agricultural	-	kg	2.28E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Copper	-	soil	agricultural	-	kg	-1.21E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Nickel	-	soil	agricultural	-	kg	-3.68E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Lead	-	soil	agricultural	-	kg	2.09E-6	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	Zinc	-	soil	agricultural	-	kg	-3.55E-5	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer application
	-	4	2,4-D	-	soil	agricultural	-	kg	2.95E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Diflubensuron	-	soil	agricultural	-	kg	2.12E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Endosulfan	-	soil	agricultural	-	kg	4.40E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Glyphosate	-	soil	agricultural	-	kg	2.20E-6	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Monocrotophos	-	soil	agricultural	-	kg	2.59E-5	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application

9.13 Cumulative Results and Interpretation

1.5.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

1.5.2 Cultivation of soybeans

Tab. 9.23 shows selected LCI results and the cumulative energy demand for the cultivation of soybeans and a comparison of these results with the ecoinvent dataset soybean, IP, at farm, CH. The differences are due to the significant higher N-fertilizer and machine usage in Switzerland. The nitrate-emissions are higher in the Swiss production. This is also caused by the higher consumption of N-fertilizers. The land occupation is lower in Brazil because two harvests per year are possible in the Brazilian soybean cultivation. An important difference between the Brazilian production on the one hand and the US and Swiss production on the other hand is the emission of CO_2 from land transformation caused by the deforestation of rainforests. The higher value in the emission of NMVOC in Brazil is also caused by the deforestation.

Tab. 9.23 Selected LCI results and the cumulative energy demand for the cultivation of soybeans

		Name		soybeans, at farm	soybeans, at farm	soy beans IP, at farm
c						
		Location		BR	US	CH
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	10.3	1.4	4.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.2	0.2	0.8
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.0	0.2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	21.2	21.2	21.4
LCI results						
resource	Land occupation	total	m2a	2.1E+0	3.9E+0	3.9E+0
air	Carbon dioxide, fossil	total	kg	1.0E-1	8.7E-2	2.9E-1
air	NMVOC	total	kg	7.5E-3	1.3E-4	4.1E-4
air	Nitrogen oxides	total	kg	1.9E-3	9.9E-4	3.0E-3
air	Sulphur dioxide	total	kg	7.7E-4	3.6E-4	6.5E-4
air	Particulates, < 2.5 um	total	kg	4.4E-3	7.5E-5	2.4E-4
air	Dinitrogen monoxide	total	kg	1.2E-3	1.4E-3	3.7E-3
air	Methane, fossil	total	kg	3.4E-3	1.3E-4	4.2E-4
water	BOD	total	kg	3.1E-4	2.8E-4	9.3E-4
soil	Cadmium	total	kg	4.0E-7	-1.8E-8	7.7E-7
water	Phosphorus	total	kg	2.8E-5	2.7E-5	9.4E-9
water	Nitrate	total	kg	3.9E-2	5.3E-2	1.7E-1
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-1.4E+0	-1.4E+0	-1.5E+0
air	Carbon dioxide, land transformation	low population density	kg	1.0E+0	1.6E-5	2.2E-5
air	Methane, biogenic	total	kg	7.7E-7	5.6E-7	1.0E-6
air	Carbon monoxide, biogenic	total	kg	1.4E-5	1.2E-5	4.1E-5

9.14 Conclusions

The life cycle inventory for the soybean cultivation in Brazil is determined largely by the transformation of tropical rain forests to agricultural area. For further work the emissions of N2O, NOx and NH3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	soybeans, at farm	soybeans, at farm
Geography	662	Location	US	BR
ReferenceFunction	493	InfrastructureProcess	0	0
ReferenceFunction	403	Unit	kg	kg
DataSetInformation	201	Type	1	1
	202	Version	1.0	1.0
	203	energyValues	0	0
	205	LanguageCode	en	en
	206	LocalLanguageCode	de	de
DataEntryBy	302	Person	24	24
	304	QualityNetwork	1	1
ReferenceFunction	400	DataSetRelatesToProduct	1	1
	402	IncludedProcesses	Cultivation of soybeans in the USA including use of diesel, machines, fertilizers, and pesticides.	Cultivation of soybeans in Brazil including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1	1
	490	LocalName	Sojabohnen, ab Hof	Sojabohnen, ab Hof
	491	Synonyms		
	492	GeneralComment	The inventory for the cultivation of soybeans in the USA is modelled with data from literature. Some data are extrapolated from Europe (production of fertilizers and pesticides) or Switzerland , (machine use). Some transports are modelled with standard distances. The functional unit is 1 kg soybeans (fresh mass with a water content of 11 %). Carbon content: 0.388 kg/kg fresh mass. Biomass energy content: 20.45 MJ/kg fresh mass. Yield: 2641 kg/ha. The emissions of N2O and NH3 to air are calculated standard factors for mineral fertilizers from Nemecek et al. 2004 and standard factors for the emission from the crop residue from Ostermayer 2002. The emission of nitrate to water is calculated with a nitrogen loss factor of 30%.	The inventory for the cultivation of soybeans in Brazil is modelled with data from literature. Some data are extrapolated from Europe (production of fertilizers and pesticides) or Switzerland , (machine use). The transports are modelled with standard distances. The functional unit is 1 kg soybeans (fresh mass with a water content of 11 %). Carbon content: 0.388 kg/kg fresh mass. Biomass energy content: 20.45 MJ/kg fresh mass. Yield: 2544 kg/ha. The emissions of N2O and NH3 to air are calculated standard factors for mineral fertilizers from Nemecek et al. 2004 and standard factors for the emission from the crop residue from Ostermayer 2002. The emission of nitrate to water is calculated with a nitrogen loss factor of 30%. The CO2 emissions caused by the transformation from tropical rainforest are calculated as "carbon dioxide, land transformation". The carbon which is bound in the tropical rainforest soil is calculated as "carbon organic matter, soil".
	494	InfrastructureIncluded	1	1
	495	Category	agricultural production	agricultural production
	496	SubCategory	plant production	plant production
	497	LocalCategory	Landwirtschaftliche Produktion	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau	Pflanzenbau
	499	Formula		
	501	StatisticalClassification		
	502	CASNumber		
TimePeriod	601	StartDate	2004	2001
	602	EndDate	2006	2006
	603	DataValidForEntirePeriod	1	1
	611	OtherPeriodText	Time of publications	Time of publications
Geography	663	Text	The inventory is modelled for the USA. Some data are extrapolated from Europe or Switzerland.	The inventory is modelled for Brazil. Some data are extrapolated from Europe or Switzerland.
Technology	692	Text	Cultivation of soybeans	Cultivation of soybeans
Representativeness	722	Percent	100	100
	724	ProductionVolume	Total production in the USA is around 82.8 Million tons.	Total production in Brazill is around 50 Million tons.
	725	SamplingProcedure	Literature data	Literature data
	726	Extrapolations	The usage of agricultural machines is extrapolated with Swiss equipment and US diesel consumption. Transports are modelled with standard distances. Emissions are calculated with standard methods.	The usage of agricultural machines is extrapolated with Swiss equipment and Brazilian diesel consumption. Transports are modelled with standard distances. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none	en
DataGeneratorAndPublication	751	Person	24	24
	756	DataPublishedIn	2	2
	757	ReferenceToPublishedSource	40	40
	758	Copyright	1	1
	759	AccessRestrictedTo	0	0
	760	CompanyCode		
	761	CountryCode		
	762	PageNumbers	bioenergy	bioenergy

References

Achard et al. 2002	Achard, F., H. D. Eva, H. J. Stibig, P. Mayaux, J. Gallego, T. Richards, and J. P. Malingreau (2002): Determination of deforestation rates of the world's humid tropical forests. Science 297: 999–1002.

Altieri et al. 2006	Altieri, M., Pengue, W.(2006): GM soybean: Latin America´s new colonizer. Seedling January 2006. http://www.grain.org/seedling
Bickel 2003	Bickel, U., Dros, J. M. (2003): The impacts of soybean cultivation on Brazilian ecosystems. Three case studies. World Wildlife Fund. Forest Conversion Initiative
Cederberg 2001	Cederberg, C., Darelius, K. (2001): Livscykelanalys (LCA) av griskött. Naturresursforum. Langstinget Halland
FAO 2004	FAO 2004: Fertilizer Use by Crop in Brazil. Land and Plant Nutrition Management Service. Land and Water Development Division FAO, Rome
FAOSTAT 2006	Faostat Database Query: Soybean Production. Retrieved 12. June 2006, from http://faostat.fao.org/faostat/
Fearnside 2000	Fearnside, P. M. (2000): Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46: 115–158
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Houghton et al. 2000	Houghton, R. A., D. L. Skole, C. A. Nobre, J. L. Hackler, K. T. Lawrence, and W. H. Chomentowski (2000): Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. Nature., 403, 301–304.
IFA 2006	IFA (2006): World Fertilizer Use Manual. Retrieved 12. June 2006, from http://www.fertilizer.org/ifa
NASS 2005	National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture. Crop Production. Released November 10, 2005
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
NREL 2006	National Rewnewable Energy Laboratory (2006): U.S. Life-Cycle Inventory Database. Retrieved 12. June 2006, from http://hpb-1a.nrel.gov/lci
Ostermayer 2002	Ostermayer, Axel: Ökobilanz für DL-Methionin in der Geflügelmast. Endbericht im Auftrag der Degussa AG. Institut für Energie- und Umweltforschung Heidelberg, Heidelberg 2002
Spielmann 2004	Spielmann M., Kägi T., Stadler P. and Tietje O. (2004) Life Cycle Inventories of Transport Services. Final report ecoinvent 2000 No. 14. UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
USDA 2004a	United States Department of Agriculture. National Agricultural Statistics Service: Agricultural Chemical Usage 2003. Field Crops Summary. May 2004
USDA 2004b	United States Department of Agriculture (2004): Brazil: Soybean expansion expected to continue in 2004/05. Production Estimates and Crop Assessment Division. August 2004

10 Sugar cane, production in Brazil

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10.1 Introduction

Sugar cane (*Saccharum officinarum* L.) is a tropical plant from the family *Poaceae*. It is cultivated between the lines of latitude 36 °N and 31 °S. For optimal growing four to five months with 30 - 35° C and an annual precipitation of 2000 mm are needed. The concentration of sugar is increased, if the temperatures in the two months before harvestings are lower (Fageria et al. 1997).

Sugar cane can be cultivated on every type of soil, but the quality of the juice differs with the soil properties. Lower yields and lower quality of the juice are achieved on acid soils. Generally sugar cane can be cultivated at a pH-value of 4 to 9 (Fageria et al. 1997). The red soils in the Brazilian state São Paulo (type lactosol) are particularly suitable for production of sugar cane.

Today 85 % of the Brazilian sugar cane is cultivated in the regions "Middle South" or "Centre South" (in the states Saõ Paulo, Minas Gerais, Rio de Janeiro Goiás, Mato Grosso do Sul, and Paraná). The other 15 % are cultivated in the North and the North East (in the states Rio Grande, Paraiba, Pernambuco, Alagoas und Sergipe) (Mathias 2005, UNICA 2004).

For this inventory the functional unit is 1 kg of sugar cane (fresh matter), at farm, BR. The contents of sugar cane are given in Tab. 10.1.

Tab. 10.1 Contents of sugar cane (Copersucar 2006, Tuchschmid 2005)

Property	Value	Unit
Water [1]	0.714	Kg/kg sugar cane fresh matter
Ligneous fibres [1]	0.14	Kg/kg sugar cane fresh matter
Saccharose [1]	0.14	Kg/kg sugar cane fresh matter
Impurities [1]	0.02	Kg/kg sugar cane fresh matter
C content [1]	0.12	Kg/kg sugar cane fresh matter
HHV [1]	4.95	MJ/kg sugar cane fresh matter
Cd [2]	5.13E-04	mg/kg sugar cane fresh matter
Cr [2]	2.57E-03	mg/kg sugar cane fresh matter
Cu [2]	1.28E-02	mg/kg sugar cane fresh matter
Ni [2]	5.13E-03	mg/kg sugar cane fresh matter
Pb [2]	2.57E-03	mg/kg sugar cane fresh matter
Zn [2]	6.41E-02	mg/kg sugar cane fresh matter

1: Source: Copersucar 2006, Tuchschmid 2005¨

2: Extrapolated from heavy metal contents of miscanthus

10.2 Farming Systems

Tab. 10.2 Types of harvesting (Macedo 1998, Paiva 2005)

Type	Brazil	Centre South
Manual harvest	80 %	65.2 %
Mechanical harvest	20 %	34.8 %
Burning		79.1 %
No burning		20.9 %

The burning of the fields causes some problems: 3 % of the sugar contained in the sugar cane is burned up, the emissions of methane and carbon monoxide are caused by the burning, and there are several negative effects on the flora, the fauna, and human health. Because of this the State Sao Paolo has acceptilated the Law No. 11241 (Estado Sao Paolo 2002). According to this law the harvesting should be changed step-by-step to 100 % mechanical harvesting in 2021. This long time is due to the great quantities of jobs, which will get lost.

10.3 Yields

FAOSTAT 2004 report an average yield of 73.6 t per ha and year in Brazil. In the region in the north of Sao Paolo the yields are a little higher with 80 t/ha*a (Granelli 2005). In Macedo 1996 values are given for the state Sao Paolo. With larger areas under cultivation the yields increase because investments for increasing productivity are more profitable.

In Tab. 10.3 values for the yields are given from several sources. In this study the average yield is calculated with the average value of Macedo 2004.

Tab. 10.3 Yields of the sugar cane cultivation

Source	Yield (t/ha*a)
FAOSTAT 2004	73.6
Macedo 1996	68.7
Granelli 2005	80
Acropecuaria Cresciumal 1998	91
Luiz 1996	90
Macedo 2004	68.7
This study	68.7

The yields decrease over the years. Macedo 2004 gives values for the yields in the years 1998 - 2002

Tab. 10.4 Yields of the sugar cane cultivation over the years after the planting (Macedo 2004)

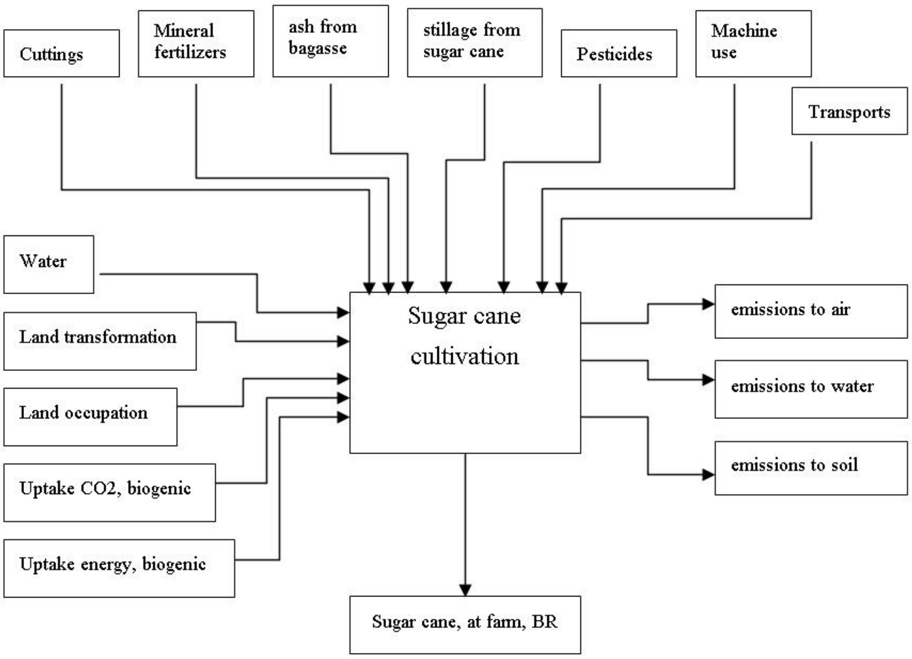
Harvest	Yield (t/ha*a)
1. Cutting (20% after 12 months, 80% after 18 months)	106
2. Cutting	90
3. Cutting	78
4. Cutting	71
5. Cutting	67

10.4 System Characterisation

This report corresponds to the dataset for the production of **1 kg sugar cane, at farm, in Brazil**.

All data in the present report are referred to 1 kg sugar cane fresh matter. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of the raw materials. Storage and transportation of the final product are not included. The emissions into water are assumed to be emitted into ground water and rivers.

Fig. 10.1 Process flow chart for the cultivation of sugar cane in Brazil



10.5 Raw materials and auxiliaries

10.5.1 Fertilizers

Lima 1987 report, that sugar cane plants are able to absorb and fix nitrogen from the air. This has been verified by Urquiaga et al. 1992 (quoted in Martins 2000). The eluviation of nitrogen is estimated at 15 kg/ha. Only 3 kg/ha depend from the fertilizer (Reichardt et al. 1982, quoted in Martins 2000).

In Tab. 10.5 quantities for the fertilizer use in Brazil are given. The application of the stillage is not included in this table.

Tab. 10.5 Fertilizer use in the sugar cane cultivation in Brazil (FAO 2004)

Region	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]
North	14	28	63
North East	31	30	79
Centre-West	57	60	130
South East	61	57	118
Centre South	76	45	113
Average (this study)	55	51	110
Ortolan 2005	60 – 73	20-30	75-110
Macedo 1996	78	44	120

Tab. 10.6 Fertilizer use by product in Brazil (FAO 2004)

Nutrient	Product	%
N	Ammonium sulphate	16
	Urea	48
	Ammonium nitrate	16
	MAP/DAP	14
	NK	1
	NPK	5
P2O5	MAP/DAP	45
	SSP	29
	TSP	16
	Thermophosphate	1
	Reactive phosphate rock	4
	NPK	5
K2O	Potassium chloride	98
	Potassium sulphate	1
	NK	1

Tab. 10.7 Use of fertilizers in the cultivation of sugar cane in this study (FAO 2004)

Product	kg kg^{-1} sugar cane
ammonium sulphate as N	1.33E-04
urea as N	3.98E-04
ammonium nitrate phosphate as N	1.33E-04
diammonium phosphate as N	1.58E-04
potassium nitrate as N	8.30E-06
diammonium phosphate as P2O5	3.46E-04
single superphosphate as P2O5	2.23E-04
triple superphosphate as P2O5	1.23E-04
phosphate rock as P2O5, MA	3.85E-05
potassium chloride as K2O	1.63E-03
potassium sulphate as K2O	1.66E-05
potassium nitrate as K2O	1.66E-05
Total mineral fertilizers	**3.26E-03**
Stillage from sugar cane	1.5083
lime from carbonation	5.20E-03
ash	6E-03

Limestone

Macedo (1996) reports an amount of 2200 kg lime per ha within 5 years for the neutralization of the pH value in the soil. This results in a quantity of 440 kg/ha*a. CRC Sugar 2002 report 1.25 t per 5 years, which results in a value of 250 kg lime per year and ha.

Ash

The ash from bagasse burning in the sugar cane processing plants is used as fertilizer in the sugar cane cultivation. Per kg sugar cane 0.006 kg ash is used. The composition of the ash is given here.

Tab. 10.8 Composition of the ash from bagasse burning (Bichara 1990)

Content	%
P2O5	0,87
K2O	1,67
CaO	0,99
MgO	0,56
Fe2O3	2,24
Al2O3	5,81
MnO	2,64
SiO2	85,22

Stillage

The stillage is applied to the soil as an additional fertilizer (Borreroa 2003, Granelli 2005).

According to Macedo (1996) a stillage amount of 100 m^3/ha*a is applied. This ameliorated the soil properties like the availability of nutrients, the capacity of cation exchange, the soil structure and the microbiological activity (Kiehl 1985, quoted in Bichara 1990)

By the application of the stillage on the fields mineral fertilizer can be substituted: nitrogen around 7.5 %, P_2O_5 around 2.2 %, and K_2O around 29.4 % (Bichara 1990). The chemical composition of stillage is given in Tab. 10.9.

Tab. 10.9 Properties of the stillage from sugar cane processing (reported in Bichara 1990)

Chemical Properties	Rodella 1980	Vasconcelos 1981	This study (average)
N [g/l]	0.28	0.26	0.27
P_2O_5 [g/l]	0.09	0.49	0.29
K_2O [g/l]	1.29	1.72	1.22
C [g/l]	6.7	7.58	7.14
Fe [ppm]	na	51.22	51.22
pH	3.7	3.57	3.635

10.5.2 Water

Within direct questionings of the farmers it was stated that in the state São Paulo the sugar cane fields are not irrigated (Granelli 2005, Luiz 1996, Marcello 2005). Only the stillage is applied in the surrounding areas of the factories. The stillage is either transferred by pipelines (de Reynier 2005) or is directly transported by trucks to the fields and is applied there (Ferrero 2005).

10.5.3 Pesticides and Biological Control

The most important parasites are Migdolus spp., leaf-cutter ants, and termites. According to Macedo (1996) only 15.25 % of the sugar cane areas are treated with pesticides, whereby 8 l/ha of endosulfan is used against soil parasites, which results in 1.22 l endosulfan per ha of the total area.

CETESB (1988) report a pesticide application of 2.4 kg/ha and a herbicide application of 2.36 kg/ha in 1983. No fungicides have been used. In this study the values, which are given in CETESB 1988, are used.

Tab. 10.10 Pesticides use in three farms in Brazil (CETESB 1988)

Farm	**Usina da Barra**	**Sao Manuel**	**Taquarituba**	**Average (this study)**	**Used dataset**
Area	11259 ha	27024 ha	873 ha		
Pesticides	[kg/ha/y]	[kg/ha/y]	[kg/ha/y]	[kg/ha/y]	
Gesapax-500	0.67	0.00	0.79	0.487	Triazine-compounds
U46	0.46	0.00	0.00	0.153	Phenoxy-compounds
RoundUp	0.26	0.40	0.00	0.22	Glyphopsate
Daconate	0.33	0.76	0.00	0.363	Pesticides, unspecified
Diuron	0.28	0.00	0.26	0.18	Diuron
Gesapax-80	0.10	0.30	0.00	0.133	Triazine-compounds
Laco	0.00	0.61	0.00	0.203	Pesticides, unspecified
Perflan	0.00	0.50	0.00	0.167	Pesticides, unspecified
Karmex	0.00	1.01	0.00	0.337	Diuron
Other Herbicides	0.16	0.06	0.12	0.113	Pesticides, unspecified
Aldrin	2.74	3.03	1.32	2.363	Pesticides, unspecified
Other insecticides	0.00	0.00	0.10	0.033	Pesticides, unspecified
Total pesticides				**4.753**	

Tab. 10.11 Use of pesticides in the cultivation of sugar cane in this study

Product	**kg kg^{-1} sugar cane**
Triazine-compounds	9.35E06
Phenoxy-compounds	2.31E-06
Glyphosate	3.32E06
Diuron	7.79E-06
Pesticides, unspecified	4.89E-05
Total pesticides	**7.17E-05**

10.5.4 Seed

About 12 t cuttings per ha are used (Granelli 2005). They are normally produced in huge professional cutting-breeding farms (Luiz 1996). The use of the cuttings is included in the calculation of the sugar cane by reducing the yields.

Tab. 10.12 Calculation of the yield with the use of cuttings included

	t ha^{-1}
yield per year	68.7
yield in 5 years (sum)	343.5
cuttings	12
difference	331.5
reduced yield per year	66.3

10.6 Energy and machine usage

Cultivation

Macedo 1996 reports data for the machine use, the processings and the diesel consumption of the cultivation of sugar cane. The values, which are used for the processes, are extrapolated from the diesel use of the datasets.

Tab. 10.13 Machine use and diesel consumption in the sugar cane cultivation (Macedo 1996)

Process	Diesel consumption	Used field process
	[l/ha/y]	
Year 1		
Limestone application	0.67	fertilizing
Stubble elimination	0.97	harrowing
Harrowing I	2.79	harrowing
Ploughing	3.14	ploughing
Harrowing II	2.71	harrowing
Harrowing III	1.89	harrowing
Harrowing IV	1.03	harrowing
Furrowing/fertilizing	1.83	fertilizing
Planting	0.84	planting
Cane covering/ pesticide application	0.38	application plant protection
Chemical cultivation	0.24	harrowing
Mechanical cultivation	0.76	harrowing
Year 2 - 5		
Waste accumulation	2.19	harrowing
Soil cultivation	4.49	harrowing
Herbicide application	1.21	application plant protection
Together	25.14	

Tab. 10.14 Machine use in the sugar cane cultivation (Macedo 1996)

Process	Diesel consumption	Machine use	Machine use
	[kg/ha/y]	[ha/a]	[ha/kg sugar cane]
fertilizing	5.29	7.9E-02	1.2E-06
tillage, harrowing	4.44	0.64	9.6E-06
tillage, ploughing	26.1	0.02	3.0E-07
planting	16.8	8.E-03	1.3E-07
Application plant protection	1.76	1.75E-01	2.6E-06

Harvesting

The diesel consumption for sugar cane harvesting depends on the harvesting technique. If it is harvested mechanically a combine harvester is used. If the sugar cane is harvested by hand only a cane loader is needed. The values, which are used for the processes, are extrapolated from the diesel use of the datasets. No electricity is needed for the cultivation and harvesting of sugar cane (Tuchschmid 2005).

Tab. 10.15 Machine use and diesel consumption for the harvest of sugar cane (Macedo 1996)

Process	Diesel [l/ha/y]	Used dataset
Mechanical harvest	75.4	Complete harvester, beets
Manual harvest	12.9	Fodder loading

Tab. 10.16 Machine use for the harvest of sugar cane in Brazil

Process	Diesel consumption	%	per 5 years	per year	per kg sugar cane
	[kg/ha/y]		[ha]	[ha]	[ha]
Complete harvester, beets	103	20	1.2E-01	2.5E-02	3.7E-07
Fodder loading [m^3]	10.6	80	8.2E-01	1.6E-01	2.5E-06

10.7 Transportation

Macedo 1996 reports transport distances (farm to field: 16 km) for several processes. For the transports to the farm the standard distances, which are given in Frischknecht 2003, are used.

Tab. 10.17 Transports amounts of raw materials and auxiliaries per kg sugar cane (Macedo 1996)

Process	Lorry 16 t [tkm]	Lorry 32t [tkm]	Rail [tkm]
Cuttings	5.79E-04	3.62E-03	-
Fertilizers	5.21E-05	3.26E-04	1.95E-03
Pesticides	1.15E-06	7.17E-06	4.30E-05
Limestone	8.33E-05	5.20E-04	3.12E-03
Total	7.16E-04	4.47E-03	5.12E-03

Tab. 10.18 Transports of the stillage (Macedo 1996)

Process	Proportion	Distance	Diesel consumption	Used dataset
	[%]	[km]	[l/ha/y]	
Distribution with tractor	49	7	42.4	Transport tractor
Distribution with sprinkler	22		20	Slurry spreading
Distribution with lorry and sprinkler	11.6	10	33.3	Lorry 32t
Distribution with lorry and sprinkler	17.4	25	38.46	Lorry 32t

Tab. 10.19 Transport amounts for the distribution of the stillage in Brazil

Transport process	per ha	per kg sugar cane
Transport tractor and trailer [tkm]	343	5.17E-03
Slurry spreading [m^3]	22	3.32E-04
Lorry 32t [tkm]	551	8.31E-03

10.8 Land use

Land use for sugar cane cultivation was 55700 km^2 in 2004 (FAOSTAT 2004). 33000 km^2 (60 %) are located in the state Sao Paolo (UNICA 2005)

1996 about 50 % or 26900 km^2 of the total cultivated sugar cane was used for ethanol production (UNICA 2005), which corresponds to 4,8 % of the total cultivated area of Brazil (without pastureland).

In the last 25 years the area for sugar cane cultivation has increased at an average of 0.97 % per year. The increase up to 2010 is expected to be around 9 % per year (Mathias 2005).

It is expected that in the next 5 years the demand for Brazilian ethanol and that the area for the cultivation of sugar cane rises substantially because of the increasing inland market and the export (Bertelli 2005, Mathias 2005).

For this reason new areas for sugar cane cultivation are examined in Brazil (Balleti, 2005). The arable land in the states Minas Gerais, Rio da Janeiro, and Sao Paulo have been found as the best. Currently 5.5 million ha of new sugar cane fields are planed in the states Sao Paulo, Parana und Minas Gerais, as the production costs are the smallest in this areas.

Because of an amissing infrastructure and very high rain quantities sugar cane cultivation in the Amazon rain forest in the Amazon region is rather implausible.

In 2002 from the only factory in the Amazon region (States of Amazon, Rondonia and Acre) 0,024 % of the whole Brazilian ethanol production was supplied (UNICA 2005). This quantity is negligible compared with the State of Sao Paulo, which manufactures 64 %.

Other points, which militate against sugar cane cultivation in the Amazon region are higher productions costs and worse terms of transport (Mathias 2005). The rain forest soils are hardly suitable for agriculture and the expected yields in this region are very low. So most experts do not expect, that the sugar cane cultivation is expanded to the Amazon region (Granelli 2005, Aronson 2005, Ortolan 2005).

In Tab. 10.20 the accounted amounts of land use are given. They are calculated with a yield of 66.3 t sugar cane per year and ha (68.7 tons minus 1.4 tons for the cuttings). The occupation is calculated as permanent for four and a half years. 0.97% % of the used land is calculated as transformed from shrub land.

Tab. 10.20 Amounts of land use for the cultivation of sugar cane in Brazil

Land use	per kg sugar cane
Transformation from arable, not irrigated [m^2]	1.49E-01
Transformation from shrub land, sclerophyllous [m^2]	1.46E-03
Transformation to arable, not irrigated [m^2]	1.51E-01
Occupation, arable, not irrigated [m^2]	1.36E-01

10.9 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon content of sugar cane, the emissions of methane and carbon monoxide from the burning of the fields, and the used stillage. The biomass energy is calculated from the energy content of the sugar cane.

Tab. 10.21 Uptake of CO_2 and biomass energy

	per kg sugar cane
CO_2, biogenic [kg]	4.51E-01
Energy, biomass [MJ]	4.95

10.10 Emissions to air

For the emission of NH_3, N_2O, and NO_x to air from the mineral fertilizer the emission factors according to Nemecek (2004) are used:

The NH_3-N emissions are calculated with different emissions factors for the mineral fertilizers: 8 % of the N-input for ammonium sulphate, 15 % for urea, 2 % for ammonium nitrate, and 4 % for dap, nk, and npk.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

The burning of the fields before harvesting is the most important source for emissions of methane, CO, and particles (Moreira 1999). In Tab. 10.22 values for the emissions to air from the sugar cane cultivation are given.

Tab. 10.22 Emissions to air from the sugar cane cultivation

Emission	Value	Unit	Source
NH_3-N	7.96E-05	[kg/kg sugar cane]	calculated from the N-input
N_2O	1.09E-05	[kg/kg sugar cane]	calculated from the N-input and nitrate leaching
NO_x	2.29E-06	[kg/kg sugar cane]	calculated from the N-input
CH_4	2.86E-04	[kg/kg sugar cane]	Macedo 1998
CO	3E-02	[kg/kg sugar cane]	Goldemberg 2002
Particulates > 10 µm	3E-03	[kg/kg sugar cane]	Goldemberg 2002

Other values for these emissions are given by Brazil (2004): 9.58 E-03 kg CO and 4.56 E-04 kg CH3 per kg sugar cane. As these values are based on data from 1994 the newer values, which are given by Goldemberg 2002 and Macedo 1998, are used in this study.

10.11 Emissions to water

For the phosphorus emissions to water the emission factors according to Nemecek (2004) are used. As no information is available about nitrate leaching from sugar cane fields in Brazil a rough estimation is done: the nitrate to groundwater emissions are calculated with an emission factor (2.5 % of the N contained in the fertilizer), which was modelled for sugar cane fields in Australia by Stewart (2003).

Tab. 10.23 Emissions to water from the sugar cane cultivation

Emission	Value
Phosphorus, to surface water (kg/kg sugar cane)	3.0E-06
Phosphorus, to ground water (kg/kg sugar cane)	1.1E-06
Nitrate, to ground water (kg/kg sugar cane)	2.1E-05

10.12 Emissions to soil

The applied pesticides are calculated as emissions to agricultural soil. As for the use of "pesticides unspecified" no elementary flow is available, these emissions are not accounted in this report. Daconate contains arsenic. It is therefore calculated as emission of arsenic to agricultural soil.

The differences between the inputs of heavy metals contained in the fertilizers and the outputs through harvested products are assumed to be heavy metal emissions to soil. Some heavy metals are calculated as heavy metal uptake because the outputs are higher than the inputs.

Tab. 10.24 Emissions to soil from the sugar cane cultivation

Emission	Used elementary flow	Value
Triazine compounds (kg/kg sugar cane)	Atrazine, to soil	9.35E-06
Phenoxy componds (kg/kg sugar cane)	2,4-D	2.31E-06
Glyphosate (kg/kg sugar cane)	Glyphosate	3.32E-06
Diuron (kg/kg sugar cane)	Linuron	7.79E-06
Daconate as As (kg/kg sugar cane)	Arsenic	2.54E-06
Aldrin (kg/kg sugar cane)	Aldrin	3.56E-05
Cd (kg/kg sugar cane)		2.80E-08
Cr (kg/kg sugar cane)		-2.55E-09
Cu (kg/kg sugar cane)		-3.98E-10
Ni (kg/kg sugar cane)		-5.13E-09
Pb (kg/kg sugar cane)		-2.57E-09
Zn (kg/kg sugar cane)		-6.41E-08

10.13 Soil fertilty

Sugar cane is cultivated in Brazil for several centuries and the yields per ha rise from year to year (Ortolan 2005). The company Granelli & Filhos Ltda. in Charqueada is producing ethanol since 1980, and there is no decreasing of the yields (Granelli 2005). The sugar cane fields are planted every 5 years with new cuttings. Between the last harvest (September - October) and the new planting in March legumes are usually cultivated to improve the soil by fixing nitrogen (Ortolan 2005). The are no evidences, which indicate decreasing yields in sugar cane fields (Granelli 2005). In contrast to this there are some research results, which show decreasing parameters of soil fertility in sugar cane cultivation: over 30 years pH, organic carbon, total nitrogen, available phosphorus and exchangeable calcium, magnesium and potassium in the soil were measured and evaluated in tropical soils by Hartemink (2004), who found a significant reduction of the soil fertility.

The loss of the soil fertility is attributed particularly to the wrong application by inorganic fertilizers and other nutrients, soil erosion and washing. In a further investigation Hartemink (1998) observed the change of the soil under sugar cane in New Guinea between 1979 and 1996. It determined also a significant reduction of all soil parameters. The content of organic carbon decreased in 8 of the examined 17 years by 40 %. However no reduction of the yield was observed. CRC Sugar (2002) compared a field, which was cultivated with sugar cane since 53 years with a lying close soil with natural vegetation. The pH of the sugar cane fields was around 4.7, the soil with the natural vegetation had a pH value of 5.4. Fageria 1997 report, that with each ton harvested sugar cane, 1.6 kg nitrogen, 1 kg phosphorus, and 3.4 kg potassium is removed from the soil. The parameters of the soil fertility decrease in all studies, but the yields increase however everywhere for years. For sustainable cultivation of sugar cane a suitable supply of nutrients (via fertilizers, stillage, and organic matter) and limestone is necessary (Fageria 1997, Hartemink 2004, CRC Sugar 2002)

1.6 Life cycle inventory of the sugar cane cultivation and data quality considerations

Tab. 10.25 shows life cycle inventory and the data quality indicators for the cultivation of sugar cane. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 10.25 Unit process raw data for the cultivation of sugar cane

401	InputGroup	OutputGroup	Name	Location	InfrastructureProcess	Unit	sugar cane, at farm	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location				BR			
493			InfrastructureProcess				0			
403			Unit				kg			
	-	0	sugar cane, at farm	BR	0	kg	1.00E+0			
resource, in air	4	-	Carbon dioxide, in air	-	-	kg	4.51E-1	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	-	MJ	4.95E+0	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
technosphere	5	-	ammonium sulphate, as N, at regional storehouse	RER	0	kg	1.33E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	urea, as N, at regional storehouse	RER	0	kg	3.98E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	ammonium nitrate phosphate, as N, at regional storehouse	RER	0	kg	1.33E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	diammonium phosphate, as N, at regional storehouse	RER	0	kg	1.58E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	potassium nitrate, as N, at regional storehouse	RER	0	kg	8.30E-6	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	3.46E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	single superphosphate, as P2O5, at regional storehouse	RER	0	kg	2.23E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	triple superphosphate, as P2O5, at regional storehouse	RER	0	kg	1.23E-4	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	phosphate rock, as P2O5, beneficiated, dry, at plant	MA	0	kg	3.85E-5	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	potassium chloride, as K2O, at regional storehouse	RER	0	kg	1.63E-3	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	potassium sulphate, as K2O, at regional storehouse	RER	0	kg	1.66E-5	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	potassium nitrate, as K2O, at regional storehouse	RER	0	kg	1.66E-5	1	1.05	(1,1,1,1,1,1); FAO 2004
	5	-	lime, from carbonation, at regional storehouse	CH	0	kg	5.20E-3	1	1.05	(1,1,1,1,1,1); CRC Sugar 2002
	5	-	vinasse, from sugarcane, at fermentation	BR	0	kg	1.51E+0	1	1.11	(1,1,3,1,1,1); Macedo 1996
	5	-	ash, bagasse, at fermentation plant	BR	0	kg	6.00E-3	1	1.05	(1,1,1,1,1,1); Tuchschmid 2005
	5	-	triazine-compounds, at regional storehouse	RER	0	kg	9.35E-6	1	1.13	(1,1,3,3,1,3); Literature 1998
	5	-	phenoxy-compounds, at regional storehouse	RER	0	kg	2.31E-6	1	1.13	(1,1,3,3,1,3); Literature 1998
	5	-	glyphosate, at regional storehouse	RER	0	kg	3.32E-6	1	1.13	(1,1,3,3,1,3); CETESB 1988
	5	-	diuron, at regional storehouse	RER	0	kg	7.79E-6	1	1.13	(1,1,3,3,1,3); CETESB 1988
	5	-	pesticide unspecified, at regional storehouse	RER	0	kg	4.89E-5	1	1.13	(1,1,3,3,1,3); CETESB 1988
	5	-	fertilising, by broadcaster	CH	0	ha	1.20E-6	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	tillage, harrowing, by spring tine harrow	CH	0	ha	9.60E-6	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	tillage, ploughing	CH	0	ha	3.05E-7	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	planting	CH	0	ha	1.27E-7	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	application of plant protection products, by field sprayer	CH	0	ha	2.63E-6	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	harvesting, by complete harvester, beets	CH	0	ha	3.71E-7	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	fodder loading, by self-loading trailer	CH	0	m3	2.47E-6	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	transport, tractor and trailer	CH	0	tkm	5.17E-3	1	2.05	(1,1,4,1,1,1); Macedo 1996
	5	-	slurry spreading, by vacuum tanker	CH	0	m3	3.32E-4	1	1.21	(1,1,4,1,1,1); Macedo 1996
	5	-	transport, lorry 16t	RER	0	tkm	5.79E-4	1	2.05	(1,1,4,1,1,1); Macedo 1996
	5	-	transport, lorry 32t	RER	0	tkm	1.28E-2	1	2.05	(1,1,4,1,1,1); Macedo 1996
	5	-	transport, freight, rail	RER	0	tkm	5.12E-3	1	2.05	(1,1,4,1,1,1); Macedo 1996
resources	4	-	Transformation, from arable, non-irrigated	-	-	m2	1.49E-1	1	2.05	(1,3,4,3,1,1); Macedo 1996
	4	-	Transformation, from shrub land, sclerophyllous	-	-	m2	1.46E-3	1	2.05	(1,3,4,3,1,1); Macedo 1996
	4	-	Transformation, to arable, non-irrigated	-	-	m2	1.51E-1	1	2.05	(1,3,4,3,1,1); Macedo 1996
	4	-	Occupation, arable, non-irrigated	-	-	m2a	1.36E-1	1	1.56	(1,3,4,3,1,1); Macedo 1996
emission air, low population density	-	4	Ammonia	-	-	kg	7.96E-5	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	-	kg	1.09E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	-	kg	2.29E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Methane, biogenic	-	-	kg	2.86E-4	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Carbon monoxide, biogenic	-	-	kg	3.00E-2	1	5.07	(4,3,1,1,1,4); Calculated with standard method
	-	4	Particulates, > 10 um	-	-	kg	3.00E-3	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, river	-	4	Phosphorus	-	-	kg	3.01E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	-	kg	1.06E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Nitrate	-	-	kg	2.07E-5	1	1.58	(4,3,1,1,1,4); Calculated with standard method
emission agricultural soil	-	4	Atrazine	-	-	kg	9.35E-6	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	2,4-D	-	-	kg	2.31E-6	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Glyphosate	-	-	kg	3.32E-6	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Linuron	-	-	kg	7.79E-6	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Arsenic	-	-	kg	2.54E-6	1	1.58	(4,3,1,1,1,4); Calculated with standard method
	-	4	Aldrin	-	-	kg	3.56E-5	1	1.32	(4,3,1,1,1,4); Calculated with standard method
	-	4	Cadmium	-	-	kg	2.85E-8	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Chromium	-	-	kg	1.31E-11	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Copper	-	-	kg	1.39E-15	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Nickel	-	-	kg	1.35E-19	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Lead	-	-	kg	3.03E-23	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Tin	-	-	kg	2.55E-26	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input

10.14 Cumulative Results and Interpretation

10.14.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

10.14.2 Cultivation of sugar cane

Tab. 10.26 shows selected LCI results and the cumulative energy demand for the cultivation of sugar cane.

Tab. 10.26 Selected LCI results and the cumulative energy demand for the cultivation of sugar cane

		Name		sugar cane, at farm
c		Location		BR
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.2
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	5.0
LCI results				
resource	Land occupation	total	m2a	1.4E-1
air	Carbon dioxide, fossil	total	kg	1.0E-2
air	NMVOC	total	kg	1.2E-5
air	Nitrogen oxides	total	kg	6.0E-5
air	Sulphur dioxide	total	kg	3.9E-5
air	Particulates, < 2.5 um	total	kg	6.6E-6
air	Dinitrogen monoxide	total	kg	1.1E-5
air	Methane, fossil	total	kg	1.7E-5
water	BOD	total	kg	2.9E-5
soil	Cadmium	total	kg	2.8E-8
water	Phosphorus	total	kg	1.1E-6
water	Nitrate	total	kg	2.1E-5
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-4.9E-1
air	Carbon dioxide, land transformation	low population density	kg	1.8E-6
air	Methane, biogenic	total	kg	2.9E-4
air	Carbon monoxide, biogenic	total	kg	3.0E-2

Tab. 10.27 shows values for CED, non-renewable, for sugar cane, at farm, BR and values, which has been found in literature.

Tab. 10.27 Comparison of CED

	Sugar cane, at farm, BR	Sugar cane in Brazil (dos Santos 1997)	Sugar cane in Brazil (Macedo et al. 2004)	Sugar cane in Morocco (Mrini et al. 2001)
CED, non-renewable energy resources, (MJ-Eq)	0.2	0.26	0.19 – 0.2	0.46 - 1

The results of the Brazilian productions are comparable. The Moroccian results are higher because of the significant higher machine and diesel usage in Morocco.

10.15 Conclusions

The life cycle inventory for the sugar cane cultivation in Brazil is determined largely by the transformation of tropical rain forests to palm plantations. For further work more information about machine usage should be included. The emissions of N2O, NOx and NH3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information

Type	ID	Field name, IndexNumber	6800
ReferenceFunction	401	Name	sugar cane, at farm
Geography	662	Location	BR
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatic	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of sugar cane in Brazil including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1
	490	LocalName	Zuckerrohr, ab Hof
	491	Synonyms	
	492	GeneralComment	The inventory for the cultivation of sugar cane in Brazil is modelled with data from literature. The functional unit is 1 kg sugar cane (fresh mass with a water content of 71.4 %). Carbon content: 0.12 kg/kg fresh mass. Biomass energy content: 4.95 MJ/kg fresh mass. Yield: 66300 kg/ha. The emissions of N2O and NH3 to air are calculated standard factors for mineral fertilizers from Nemecek et al. 2004. The emissions of methane and carbon monoxide to air are calculated with emission factors from Moreira 1999. The emission of nitrate to water is calculated with a nitrogen loss factor of 2.5%.
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1996
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications
Geography	663	Text	The inventory is modelled for Brazil
Technology	692	Text	Cultivation of sugar cane with 20 % mechanical harvest and 80 % manuall harvest
Representativene	722	Percent	100
	724	ProductionVolume	Total production in Brazil is around 268 Million tons.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	sugar cane

References

Acropecuaria Cresciumal 1998 Acropecuaria Cresciumal S.A. (1998). Acropecuaria Cresciumal S.A. (1998). Usina e Acropecuaria Cresciumal S.A.

Agroquímica 2005 Agroquímica, U. (2005). Resultado de Programa UBYFOL de Nutriçao Foliar na Cultura da Canade-Açúcar.Uberaba: Uby Agroquímica Ltda.

Anselmi 2005a	Anselmi, R. (2005). Novas perspectivas para a biomassa de cana. Jornalcana, 141, 58.
Anselmi 2005b	Anselmi, R. (2005). Tecnologia de concentração de vinhaça e destaque. Jornalcana, 141, 56.
Aronson 2005	Interview with D. Aronson at the booth of Petrobras, Fenasucro 2005. Personal communication from Matthias Tuchschmidt and Stefanie Steiner 2005
Balleti 2005	Balleti, L. (2005). Gerenciamento Espacial. ALCOOLbrás, Agosto de 2005.
Bertelli 2005	Bertelli, L. G. (2005). Álcool barato compensa petróleo caro. Jornalcana, 141, 128.
Bichara 1990	Bichara, J. M., & Filho, J. P. (1990). Aspectos Gerais do Gerenciamento Ambiental na Agroindústria canavieira. Paper presented at the I Simpósio Nacional de Gerenciamento Ambiental na Indústria, Brasilia.
Borreroa 2003	Borreroa, M. A. V., et al. (2003). An environmental management method for sugar cane alcohol production in Brazil. Biomass and Bioenergy, 25, 287 – 299.
Brazil 2004	Ministry of Science and Technology (2004): Brazil's initial national communication to the United Nations framework convention on climate change. General Coordination om Global Climate Change, Brasilia
CETESB 1988	CETESB. (1988). Planejamento do uso racional das Áreas Agropastoris nas APA's com Destaque para as áreas Canavieiras.São Paulo: Compania de Tecnologia de Saneamento Ambiental -CETESP.
Copersucar 2005	Copersucar. (2005). Usinas de açúgar e álcool. Retrieved 29.8.05, 2005. from http://www.copersucar.com.br
Copersucar 2006	Sugar cane. Copersucar 2006. Retrieved 31.03.2006 from http://www.copersucar.com.br/
CRC Sugar 2002	CRC Sugar. (2002). Improving the Health of difficult Soils: Managing Soil Acidification. Retrieved 10.10.2005, 2005, from http://wwwsugar.jcu.edu.au/images/publications/info_sheets/16.%20Improving%20the%20Health%20of%20Difficult%20Soils.pdf
de Reynier 2005	de Reynier, A. (2005). Einsatz von Edra-Rohren zur Verteilung der Vinasse in Zuckerrohrfabriken.Ipeúna, SP, Brasilien.
Deepchand 1986	Deepchand, K. (1986). Characteristics, Present Use and Potential of Sugar Cane Tops and Leaves. Agricultural Wastes, 15, 139-148.
Estado São Paulo 2002	Estado São Paulo. (2002). Lei N. 11241, de 19 de Setembro de 2002, Dispõe sobre a eliminação do uso do fogo como método despalhador e facillitador do corte da cana-de-açúcar (Vol. 11241, pp. 4): O Gorvernador do Estado de São Paulo.
Fageria 1997	Fageria, N. K., et al. (1997). Growth and Mineral Nutrition of Field Crops (2 ed.). New York: Dekker.
FAO 2004	FAO (2004). Fertilizer Use by Crop in Brazil. from http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/007/y5376e/y5376e06.htm
FAOSTAT 2004	FAOSTAT. (2004). Faostat Database Query: Sugarcane Production in Brazil 1961-2004. Retrieved 14. August, 2005, from http://faostat.fao.org/faostat/
Ferrero 2005	Ferrero, M., & Gonzaga, J. L. (2005). Nova Solução para a vinhaça. IDEA News – Atualizando executivos, Setembro, 122.
Finanzdepartement 2005	Eidgenössisches Finanzdepartement. (2005). Bioethanol - ein Treibstoff mit Zukunft. Retrieved 10.10.2005, 2005, from

	http://www.efd.admin.ch/d/dok/faktenblaetter/efdschwerpunkte/7_bioethanol.htm
Freire 2005	Freire, W. R. (2005). A Hora é agora. ALOOLbrás, Agosto 2005.
Frischknecht 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Goldemberg 2002	Goldemberg, J. (2002). A Lei das Queimadas. Retrieved 10.10.2005, 2005, from http://www.cptec.inpe.br/products/queimadas/documentos/goldembergj.txt
Granelli 2005	Granelli, J. (2005). personal Communication. Industria de Alcool e Aguardente, José Granelli & Filhos Ltds, Sitio Sao Benedito Paraisolandia, Charqueada SP, Brazil.
Hartemink 1998	Hartemink, A. E. (1998). Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. Geoderma, 85, 283–306.
Hartemink 2004	Hartemink, A. E. (2004). Soil Fertility Decline on Agricultural Plantations in the Tropics. Paper presented at the IFA Regional Conference for Asia and the Pacific, Auckland, New Zealand.
Hassuda 1989	Hassuda, S. (1989). Impactos da Infiltracao da Vinhaca de Cana no Aquifero Bauru. Universidade de São Paulo, Sao Paulo.
IDEA 2005	IDEA. (2005). Mapa das Usinas. Retrieved 29.8.05, 2005, from http://www.ideaonline.com.br/
JornalCana 2005	JornalCana. (2005). Demanda pro álcool deve aumentar área de cana em 3 milhões de hectares. Jornalcana, p. 32.
Kassai 2005	Kassai, L. (8.7.2005). Cargill pode desistir da usina Corona. Agronegócio, p. 13.
Lima 1987	Lima, E., et al. (1987). Quantification of biological nitrogen fixation associated with sugar cane using a 15N aided Nitrogen Balance. Soil Biol. Biochem., 19(2), 165-170.
Luiz 1996	Luiz, J. (1996). Usina São Martinho S/A Açucar e álcool.Pradópolis.
Macedo 1996	Macedo, I. d. C. (1996). Greenhouse Gas Emissions and Avoided Emissions in the Production and Utilization of Sugar Cane, Sugar and Ethanol in Brazil: 1990-1994. from http://www.mct.gov.br/clima/ingles/comunic_old/coperal.htm
Macedo 1998	Macedo, I. d. C. (1998). Greenhouse gas emissions and energy balances in bioethanol Production and utilization in Brazil (1996). Biomass and Bioenergy, 14, 77-81.
Macedo et al. 2004	Macedo, I. d. C., Lima Verde Leal, M., Azevedo Ramos da Silva, J. (2004): Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil.São Paulo: Government of the State of São Paulo, Secretariat of the Environment.
Marcello 2005	Marcello. (2005). Neue Lösungen zur Wasserreduktion in modernen Usinas.
Martins de Oliveira 2000	Martins de Oliveira, J. C., et al. (2000). Nitrogen Dynamics in a soil-sugar cane system. Scientia Agricola, 57(3), 467-472.

Mathias 2005a	Mathias, J. (2005). Anos Dourados para a indústria de cana. Globo Rural, Ediçao Especial, 10.
Mathias 2005b	Mathias, J. (2005). A refinaria do futuro. Globo Rural, Ediçao Especial, 46.
Möllersten 2003	Möllersten, K., et al. (2003). Potential market niches for biomass energy with CO2 capture and storage--Opportunities for energy supply with negative CO2 emissions. Biomass and Bioenergy, 25(3), 273-285.
Montanini 2005	Montanini, L. (2005). Reativiaçao da ferrovia fundamental no desenvolvimento da Alta Paulista. Jornalcana, 141, 122.
Moreira 2000	Moreira, J. R. (2000). Sugarcane for energy - recent results and progress in Brasil. Energy for Sustainable Development, 4(3).
Moreira 1999	Moreira, J. R., & Goldemberg, J. (1999). The alcohol program. Energy Policy, 27(4), 229-245.
Mrini et al. 2001	Mrini, M., Senhaji F.,Pimentel D.: Environment, Development and Sustainability, Volume 3, Number 2, 2001, pp. 109-126(18) DOI: 10.1023/A:1011695731580
Nemecek 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Oanda 2005	Oanda. (2005). Currency Converter. from http://www.oanda.com/convert/classic
Ortolan 2005	Ortolan, R. B. (2005). Interview at exhibition "Fenasucro 2005", Agronom von Copercana.
Paiva 2005	Paiva, L. R. (2005). Menos fogo nos canaviais. mundodez - Responsabilidade social, ambiental e qualidade de vida, Ediçao especial, Setembro 2005.
Percebon 1985	Percebon, C. M., & Vallo de Amaral, L. A. (1985). Avaliacao da Qualidade das águas de Lavagem de Cana recilcadas em duas usinas do estado de São Paulo. Paper presented at the 13. Congresso Brasileiro de Engenharia Sanitária e Ambiental, Maceió - Alagoas.
Real 2005	Real, M. (2005). Einsatz von Bagasse als Naturfasern. Zurich.
Rocha 2005c	Rocha, M. S., & Simões-Moreira, J. R. (2005). A simple impedance method for determining ethanol and regular gasoline mixtures mass contents. Fuel, 84, 447-452.
dos Santos 1997	dos Santos, M.: Energy analysis of crops used for producing ethanol and CO2 emissions. Energy Planning Program/COPPE/UFRJ. Rio de Janeiro 1997
Sieg 2005	Sieg, K. (2005, 15. August). Zuckersüsse Alternative für den Automotor. Tages-Anzeiger.
Soares 2005a	Soares, P. (2005). De primeiro mundo - Pequisas e desenvolvimento de novas variedades e sistemas de produção colaboram para a expansão da agroindústria canavieira. Globo Rural, Ediçao Especial, 38.
Soares 2005b	Soares, P. (2005). Disparado na frente - Líder mundial na produçao e exportação da commodity, setor industrial procura mais espço para expansão no mercado internacional. Globo Rural, Ediçao Especial, 10.
Stewart 2003	Stewart, L. K., Charlesworth, P. B., Bristow, K. L. (2003): Estimating nitrate leaching under a sugarcane crop using APSIM-SWIM. In Post, D. A. (ed.) MODSIM 2003 International Congress on Modelling and Simulation. Volume 2,

	pp 218-223. Modelling and Simulation Society of Australia and New Zealand, July 2003.
Transpetro 2005	Transpetro. (2005). Fluxo do etanol para exportação - Região Sudeste.
Tuchschmidt 2005	Tuchschmid, Matthias, Steiner, Stefanie: Personal communication. Ipeuna, Brazil 2005
UNICA 2004	UNICA. (2004). Brazil's Sugar and Ethanol - Energy and Environmental Commodities.Saõ Paulo.
UNICA 2005	UNICA. (2005). Carro a álcool - Mercado. Retrieved 8. September, 2005, from http://www.portalunica.com.br/acao/combustivel.jsp

11 Sweet Sorghum, production in China

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11.1 Introduction

Sweet sorghum (*Sorgum bicolor* L. MOENCH) is a tropical crop of the family *Poaceae*. The sweet type is used mainly as livestock fodder: its high rate of photosynthesis produces leafy stalks up to 5 metres tall that make excellent silage. The stalks are also rich in sugar, which can be processed into jaggery or distilled to produce ethanol.

World production of sorghum trails far behind that of the four most important cereals (rice, maize, wheat and barley). But it is agriculture's leading minor grain crop, with the harvest in year 2005 estimated at some 60 million tones grains (FAOSTAT 2006). About 90% of the area planted with sorghum lies in developing countries, mainly in Africa and Asia, where it is grown generally for food by low-income farmers. The Chinese production is around 2.6 million tons. The remaining 10% is made up of large-scale commercial farms, most of them in the developed world, which produce sorghum mainly for livestock feed. Those farms account for more than 40% of global sorghum output.

As a food for humans, sorghum is well suited for use in the cereal, snack food, baking and brewing industries. Sorghum is also used in the production of wallboard for the housing industry and in biodegradable packaging materials. The stems can be used for ethanol production.

For this inventory the functional unit is 1 ha of sweet sorghum cultivation, CN. This is a multi-output process with sorghum grains and sorghum stem as allocated products. The properties of sorghum grains are given in Tab. 11.1 and the properties of sorghum stem are given in Tab. 11.2.

Tab. 11.1 Properties of sweet sorghum grains (Smith et al. 2000)

Property	Value	Unit
Water	0.091	kg/kg sorghum grains fresh matter
Cu	10.7	mg/kg sorghum grains fresh matter
Zn	15.2	mg/kg sorghum grains fresh matter
Carbon content	0.369	kg/kg sorghum grains fresh matter
HHV	14.27	MJ/kg sorghum grains fresh matter

Tab. 11.2 Properties of sweet sorghum stems (Dauriat 2000)

Property	Value	Unit	Remarks
Water	0.73	kg/kg sorghum stems fresh matter	Dauriat 2000
Cd	0.035	mg/kg sorghum stems fresh matter	BIOBIB 1996
Cu	1.59	mg/kg sorghum stems fresh matter	BIOBIB 1996
Pb	0.77	mg/kg sorghum stems fresh matter	BIOBIB 1996
Zn	1.84	mg/kg sorghum stems fresh matter	Smith et al. 2000
Carbon content	0.115	kg/kg sorghum stems fresh matter	
HHV	4.54	MJ/kg sorghum stems fresh matter	

11.2 Yields

Tab. 11.3 data for the sorghum cultivation in China are given. The data are based on official statistics.

Tab. 11.3 Sorghum cultivation in China

Sorghum production in China	Value
Area (ha) [1]	672600
Yield: stem (kg fm/ha) [2]	48263
Yield: Grains (kg fm/ha) [3]	3865
Total yield (kg/ha)	52128

1: FAOSTAT 2006
2: FAO 2002b
3: Average yield in the years 2001-2005 (FAOSTAT 2006)

11.3 System Characterisation

This report corresponds to the multioutput process **cultivation of sweet sorghum, at farm, in China**. The following processes are modelled:

- sweet sorghum, CN. Multioutput process with sorghum grains and sorghum stems as allocated products
- sweet sorghum grains, at farm, CN
- sweet sorghum stem, at farm, CN

All data in the present report are referred to 1 ha cultivated with sweet sorghum. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air, water, and soil. It also includes transportation of the raw materials, storage and transportation of the final product. The emissions into water are assumed to be emitted into ground water and rivers.

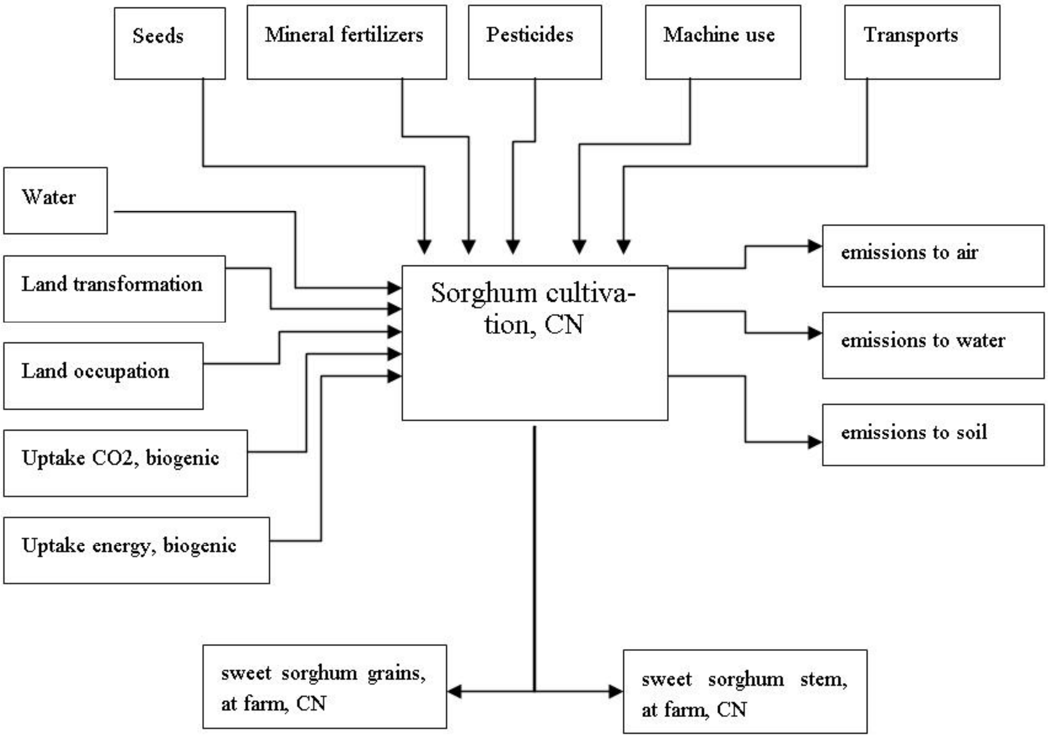


Fig. 11.1 Process flow chart for the cultivation of sweet sorghum in China

11.4 Raw materials and auxiliaries

1.6.1 Fertilizers

In Tab. 11.4 quantities for the fertilizer use in the sorghum cultivation in China are given. The data from IFA (2006) are based on expert estimations. As N fertilizers only urea and ammonia nitrate are used in the calculation.

Dauriat (2000) estimates an amount of 300 kg lime per ha and year for the neutralization of the pH value in the soil in China. This value is also used for this study.

Tab. 11.4 Fertilizer use in the sorghum cultivation in China (IFA 2006)

Fertilizer	N [kg/ha/y]	P2O5 [kg/ha/y]	K2O [kg/ha/y]
Sorghum cultivation in China	80	50	50

Tab. 11.5 Fertilizer use by product (IFA 2006)

Nutrient	Product	%
N	Urea	50
	Ammonium nitrate	29
	Others	21
P2O5	TSP	100
K2O	Potassium chloride	100

Tab. 11.6 Use of fertilizers in the cultivation of sorghum in this study

Product	kg ha^{-1}
urea as N	40
ammonium nitrate as N	40
diammonium phosphate as P2O5	50
potassium chloride as K2O	50
limestone	300

1.6.2 Water

The sorghum fields China are irrigated. Smith et al. (2000) reports an amount of 1500 m^3 water per ha. In this study the irrigation is calculated with the dataset “irrigating" (Nemecek et al. 2004). The value is calculated from the water use of the irrigating dataset.

1.6.3 Pesticides and Biological Control

USDA (2004) reports amounts of pesticides use in the sorghum cultivation in the USA. As no specific data are available for China, these data are used for this study. They are given here.

Tab. 11.7 Pesticides use in the sorghum cultivation (USDA 2004)

Pesticide group	Pesticide	Amount [kg/ha/y]	Used dataset
Herbicides	2,4-D	0.0745	2,4-D
	Alachlor	0.276	Alachlor
	Atrazine	0.816	Atrazine
	Dicamba	0.013	Dicamba
	Dimethenamid	0.076	acetamide-anilide-compounds
	Glyphosate	0.245	Glyphosate
	Metolachlor	0.095	Metolachlor
	Metsulfuron-methyl	0.000168	sulfonyl-urea-compounds
	Prosulfuron	0.00135	sulfonyl-urea-compounds
	S-Metolachlor	0.269	Metolachlor
Insecticides	Chlorpyrifos	0.00807	organophosphorus-compounds
	Terbufos	0.0210	organophosphorus-compounds
Pesticides total		1.89	

Tab. 11.8 Use of pesticides in the cultivation of sorghum in this study

Product	kg ha^{-1}
2,4-D	7.45E-02
Alachlor	2.76E-01
Atrazine	8.16E-01
Dicamba	1.26E-02
acetamide-anilide-compounds	7.61E-02
Glyphosate	2.45E-01
Metolachlor	3.64E-01
sulfonyl-urea-compounds	1.51E-03
organophosphorus-compounds	2.91E-02
Pesticides together	1.89

1.6.4 Seed

About 5 kg seeds per ha are used (Smith et al. 2000). The use of the seeds is included in the calculation of the sorghum cultivation by reducing the yields.

Tab. 11.9 Calculation of the yield with the use of seeds included

	kg ha^{-1}
Grain yield per year	3865
seeds	5
reduced grain yield per year	3860

11.5 Energy and machine usage

Cultivation

FAO (2002a) reports data for the processings of the cultivation of sorghum in China. The machine usage is calculated with values for the diesel consumption from Nemecek et al. (2004), which give data for agricultural processes in Switzerland. The values, which are used for the processes, are calculated from the land use.

Tab. 11.10 Machine use in the sorghum cultivation

Process (FAO 2002a)	**Diesel consumption of the field works** (Nemecek et al. 2004)	**Machine usage**
	[kg/ha]	[ha/ha sorghum]
Fertilizing (3x)	5.29	0.33
Ploughing (1x)	26.11	1
harrowing	4.44	1
currying	1.6	1
sowing	3.82	1
application plant protection (3x)	1.76	0.33
combine harvesting	33.31	1
chiseling	15.52	1

11.6 Transportation

For the transports the standard distances, which are given in Nemecek et al. (2004), are used. Pesticides and fertilizers are converted into the product weight in order to calculate the requirements for transports in tkm. For pesticides a mean active-ingredient content of 50 % is used according to Nemecek et al. (2004). For the fertilizers the average nutrient contents are used, which are given in Nemecek et al. (2004).

Tab. 11.11 Transports distances in sorghum cultivation

Material	Tractor and trailer [km]	Lorry 28t [km]	Lorry 32t [km]	Rail [km]	Barge [km]
Seeds	15[1]	-	-	-	-
N-Fertilizers	-	100[1]	-	100[1]	900[1]
P-Fertilizers		100[1]	-	100[1]	400[1]
K-Fertilizers		100[1]	-	100[1]	100[1]
Pesticides	15[1]		-	-	-
Limestone	15[1]		100[2]	600[2]	-
sorghum	15[1]	-		-	-

Source:

1: Nemecek et al. (2004)

2: Frischknecht et al. (2003)

Tab. 11.12 Transport service requirements of raw materials and auxiliaries in sorghum cultivation

Material	[tkm/ha]
lorry 28t [tkm]	43
lorry 32t [tkm]	30
rail [tkm]	223
barge [tkm]	268.2
tractor and trailer [tkm]	786.4

11.7 Land use

According to Nemecek et al. (2004), land occupation was calculated from the duration of land use (taking the time from soil cultivation until harvest into account). The land occupied is always considered as “Occupation, arable”.

Land transformation is calculated on the basis of 1 ha area cultivated with sweet sorghum. The type of use before establishment of the crop is assumed to be arable land.

In Tab. 11.13 the accounted amounts of land use are given. The occupation is calculated during 7 months per year (Smith et al. 2000).

Tab. 11.13 Amounts of land use for the cultivation of sorghum

Land use	per ha sorghum
Transformation from arable [m2]	10000
Transformation to arable [m2]	10000
Occupation, arable, irrigated [m2a]	5833

11.8 CO_2-uptake and biomass energy

The uptake of CO_2 is calculated from the carbon balance. The biomass energy is calculated from the energy content of sweet sorghum.

Tab. 11.14 Uptake of CO_2 and biomass energy

	CO_2, biogenic [kg]	Energy, biomass [MJ]
per kg sorghum stem (fm)	4.22E-01	4.54
per kg sorghum grains (fm)	1.35	14.27
Total per ha	25577	2.74E05

11.9 Emissions to air

The emission factors of NH_3, N_2O, and NO_x to air from the mineral fertilizers the emission factors are used according to Nemecek et al. (2004):

The NH_3-N emissions are calculated with different emissions factors depending the mineral fertilizers: 15 % of the N contained in the fertilizer for urea and 2 % for ammonium nitrate.

The N_2O emissions are calculated with a direct emission factor of 1.25% of the N-input and an indirect emission factor of 2.5% from the N that is leached as nitrate.

The NO_x emissions are calculated from the emission of N_2O: $NO_x = 0.21 * N_2O$.

In Tab. 11.15 values for the emissions to air from sorghum cultivation are given.

Tab. 11.15 Emissions to air from sorghum cultivation

Emission	Value	Unit	Source
NH_3-N	6.8	[kg/ha]	calculated from the N-input
N_2O	3.83	[kg/ha]	calculated from the N-input and nitrate leaching
NO_x	0.81	[kg/ha]	calculated from the N-input

11.10 Emissions to water

For the phosphorus emissions to water the emission factors are calculated according to the method, which is described for Switzerland in Nemecek et al. (2004). The factors, which are used for the calculations, are taken from corn cultivation.

As no data are available for nitrate leaching, a rough estimation is done: the cultivation of sorghum is assumed to be similar to the corn cultivation. Randall et al. (2003) report a nitrogen loss of about 32 % of the N contained in the fertilizers in the corn cultivation in the USA. The N is leached as nitrate.

Tab. 11.16 Emissions to water from sorghum cultivation

Emission	**Emission factor** (% of the nutrient contained in the fertilizer)	Value
Phosphorus, to surface water (kg/ha)	0.91	6.8
Phosphorus, to ground water (kg/ha)	0.07	3.83
Nitrate, to ground water (kg/ha)	32	113.4

11.11 Emissions to soil

The applied pesticides are calculated as emissions to soil.

The differences between the inputs of heavy metals contained in the fertilizers and the seeds and the outputs through harvested products are assumed to be heavy metal emissions to soil. Because the outputs of heavy metals are higher than the inputs the emissions are calculated as heavy metal uptake from the soil.

Tab. 11.17 Emissions to soil from sorghum cultivation

Emission	Value (kg/ha)
Cd	-1.83E-03
Cu	-8.29E-02
Pb	-4E-02
Zn	-9.6E-02
2,4-D	7.45E-02
Alachlor	2.76E-01
Atrazine	8.16E-01
Dicamba	1.26E-02
Dimethenamid	7.61E-02
Glyphosate	2.45E-01
Metolachlor	3.64E-01
Metsulfuron-methyl	1.68E-04
Prosulfuron	1.35E-03
Chlorpyrifos	8.07E-03
Terbufos	2.11E-02
Total pesticides	1.89

1.7 Co-products and Allocation

Sorghum cultivation is a multi-output process with sorghum grains and sorghum stems as allocated products. The economic value is used as allocation factor. The allocation of the uptake of CO2 and energy is calculated from the carbon content and the energy content of the allocated products.

Tab. 11.18 Possible allocation parameters of the co-products from sorghum cultivation

Co-products	kg/ha	Price (yuan/kg)[1]	Economic allocation factor
sorghum grains	3860	1.4	42.7%
sorghum stems	48263	0.15	57.3 %

Source: 1: Dauriat (2006)

Tab. 11.19 Allocation factors for the co-products from sorghum cultivation

Inputs/Outputs	Grains	Stems
Inputs		
all fertilizers	42.7	57.3
all pesticides	42.7	57.3
all machine usages	42.7	57.3
all transports	42.7	57.3
land use	42.7	57.3
CO2, biogenic	20.4	79.6
Energy, biomass	20.1	79.9
Outputs		
Emissions to air	42.7	57.3
Emissions to water	42.7	57.3
Emissions to agricultural soil	42.7	57.3

1.8 Life cycle inventory of sorghum cultivation and data quality considerations

Tab. 11.20 shows the life cycle inventory and the data quality indicators for the cultivation of sweet sorghum. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 11.20 Unit process raw data of the cultivation of sweet sorghum

401	InputGroup	OutputGro	Name	Location	InfrastructureProcess	Unit	sweet sorghum	Uncertainty Type	StandardDeviation95 %	GeneralComment
662			Location				CN			
493			InfrastructureProcess				0			
403			Unit				ha			
allocated products	-	2	sweet sorghum grains, at farm	CN	0	kg	3.87E+3			
	-	2	sweet sorghum stem, at farm	CN	0	kg	4.83E+4			
resource, in air	4	-	Carbon dioxide, in air	-	-	kg	2.56E+4	1	1.24	(4,3,1,1,1,4); calculated from the carbon balance
resource, biotic	4	-	Energy, gross calorific value, in biomass	-	-	MJ	2.74E+5	1	1.24	(4,3,1,1,1,4); calculated from the energy balance
technosphere	5	-	urea, as N, at regional storehouse	RER	0	kg	4.00E+1	1	1.11	(3,1,1,1,1,1); IFA 2006
	5	-	ammonium nitrate, as N, at regional storehouse	RER	0	kg	4.00E+1	1	1.11	(3,1,1,1,1,1); IFA 2006
	5	-	diammonium phosphate, as P2O5, at regional storehouse	RER	0	kg	5.00E+1	1	1.11	(3,1,1,1,1,1); IFA 2006
	5	-	potassium chloride, as K2O, at regional storehouse	RER	0	kg	5.00E+1	1	1.11	(3,1,1,1,1,1); IFA 2006
	5	-	lime, from carbonation, at regional storehouse	CH	0	kg	3.00E+2	1	1.11	(3,1,1,1,1,1); IFA 2006
	5	-	irrigating	CH	0	ha	1.25E+0	1	1.14	(3,3,2,1,1,3); Smith 2000
	5	-	2,4-D, at regional storehouse	RER	0	kg	7.45E-2	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	alachlor, at regional storehouse	RER	0	kg	2.76E-1	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	atrazine, at regional storehouse	RER	0	kg	8.16E-1	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	dicamba, at regional storehouse	RER	0	kg	1.26E-2	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	acetamide-anillide-compounds, at regional storehouse	RER	0	kg	7.61E-2	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	glyphosate, at regional storehouse	RER	0	kg	2.45E-1	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	metolachlor, at regional storehouse	RER	0	kg	3.64E-1	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	[sulfonyl]urea-compounds, at regional storehouse	RER	0	kg	1.51E-3	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	organophosphorus-compounds, at regional storehouse	RER	0	kg	2.91E-2	1	1.07	(1,1,1,3,1,3); USDA 2004
	5	-	fertilising, by broadcaster	CH	0	ha	3.33E-1	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	tillage, ploughing	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	tillage, harrowing, by spring tine harrow	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	tillage, currying, by weeder	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	sowing	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	application of plant protection products, by field sprayer	CH	0	ha	3.33E-1	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	combine harvesting	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	tillage, cultivating, chiselling	CH	0	ha	1.00E+0	1	1.22	(1,1,4,1,1,3); FAO 2002
	5	-	transport, tractor and trailer	CH	0	tkm	4.30E+1	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, lorry 28t	CH	0	tkm	3.00E+1	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, lorry 32t	RER	0	tkm	2.23E+2	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, freight, rail	RER	0	tkm	2.68E+2	1	2.09	(4,5,na,na,na,na); Standard Distances
	5	-	transport, barge	RER	0	tkm	7.86E+2	1	2.09	(4,5,na,na,na,na); Standard Distances
resources	4	-	Transformation, from arable	-	-	m2	1.00E+4	1	2.05	(1,3,4,3,1,1); FAOSTAT 2006, FAO 1994
	4	-	Transformation, to arable	-	-	m2	1.00E+4	1	2.05	(1,3,4,3,1,1); FAOSTAT 2006, FAO 1994
	4	-	Occupation, arable	-	-	m2a	5.83E+3	1	1.56	(1,3,4,3,1,1); FAOSTAT 2006, FAO 1994
emission air, low population density	-	4	Ammonia	-	-	kg	6.80E+0	1	1.32	(4,3,1,3,1,4); Calculated with standard method
	-	4	Dinitrogen monoxide	-	-	kg	3.83E+0	1	1.58	(4,3,1,3,1,4); Calculated with standard method
	-	4	Nitrogen oxides	-	-	kg	8.05E-1	1	1.58	(4,3,1,3,1,4); Calculated with standard method
emission water, river	-	4	Phosphorus	-	-	kg	9.07E-1	1	1.58	(4,3,1,3,1,4); Calculated with standard method
emission water, ground	-	4	Phosphorus	-	-	kg	7.00E-2	1	1.58	(4,3,1,3,1,4); Calculated with standard method
	-	4	Nitrate	-	-	kg	1.13E+2	1	1.58	(4,3,1,1,1,4); Estimation
emission agricultural soil	-	4	Cadmium	-	-	kg	-1.83E-3	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Copper	-	-	kg	-8.29E-2	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Lead	-	-	kg	-4.00E-2	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	Zinc	-	-	kg	-9.60E-2	1	1.58	(4,3,1,1,1,4); Calculated from the fertilizer input
	-	4	2,4-D	-	-	kg	7.45E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Alachlor	-	-	kg	2.76E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Atrazine	-	-	kg	8.16E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Dicamba	-	-	kg	1.26E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Dimethenamid	-	-	kg	7.61E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Glyphosate	-	-	kg	2.45E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Metolachlor	-	-	kg	3.64E-1	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Metsulfuron-methyl	-	-	kg	1.68E-4	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Prosulfuron	-	-	kg	1.35E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Chlorpyrifos	-	-	kg	8.07E-3	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application
	-	4	Terbufos	-	-	kg	2.11E-2	1	1.32	(4,3,1,1,1,4); Calculated from the pesticide application

11.12 Cumulative Results and Interpretation

1.8.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al .(2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

1.8.2 Cultivation of sweet sorghum

Tab. 11.21 shows selected LCI results and the cumulative energy demand for the cultivation of sweet sorghum.

Tab. 11.21 Selected LCI results and the cumulative energy demand of the cultivation of sweet sorghum

		Name		sweet sorghum grains, at farm	sweet sorghum stem, at farm
		Location		CN	CN
		Unit	Unit	kg	kg
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	2.2	0.2
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.0	0.1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.3	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	14.3	4.5
LCI results					
resource	Land occupation	total	m2a	6.6E-1	7.1E-2
air	Carbon dioxide, fossil	total	kg	1.3E-1	1.4E-2
air	NMVOC	total	kg	1.8E-4	1.9E-5
air	Nitrogen oxides	total	kg	9.1E-4	9.7E-5
air	Sulphur dioxide	total	kg	4.5E-4	4.8E-5
air	Particulates, < 2.5 um	total	kg	9.4E-5	1.0E-5
air	Dinitrogen monoxide	total	kg	5.1E-4	5.5E-5
air	Methane, fossil	total	kg	2.4E-4	2.6E-5
water	BOD	total	kg	3.6E-4	3.8E-5
soil	Cadmium	total	kg	-2.0E-7	-2.2E-8
water	Phosphorus	total	kg	7.7E-6	8.3E-7
water	Nitrate	total	kg	1.3E-2	1.3E-3
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	-1.4E+0	-4.2E-1
air	Carbon dioxide, land transformation	low population density	kg	1.4E-5	1.5E-6
air	Methane, biogenic	total	kg	1.1E-6	1.2E-7
air	Carbon monoxide, biogenic	total	kg	8.5E-6	9.1E-7

Tab. 11.22 shows values for CED, non-renewable, for the two datasets and values, which have been found in literature. The differences are due to the lower machine usage and the lower fertilizer use, which has been considered in dos Santos 1997.

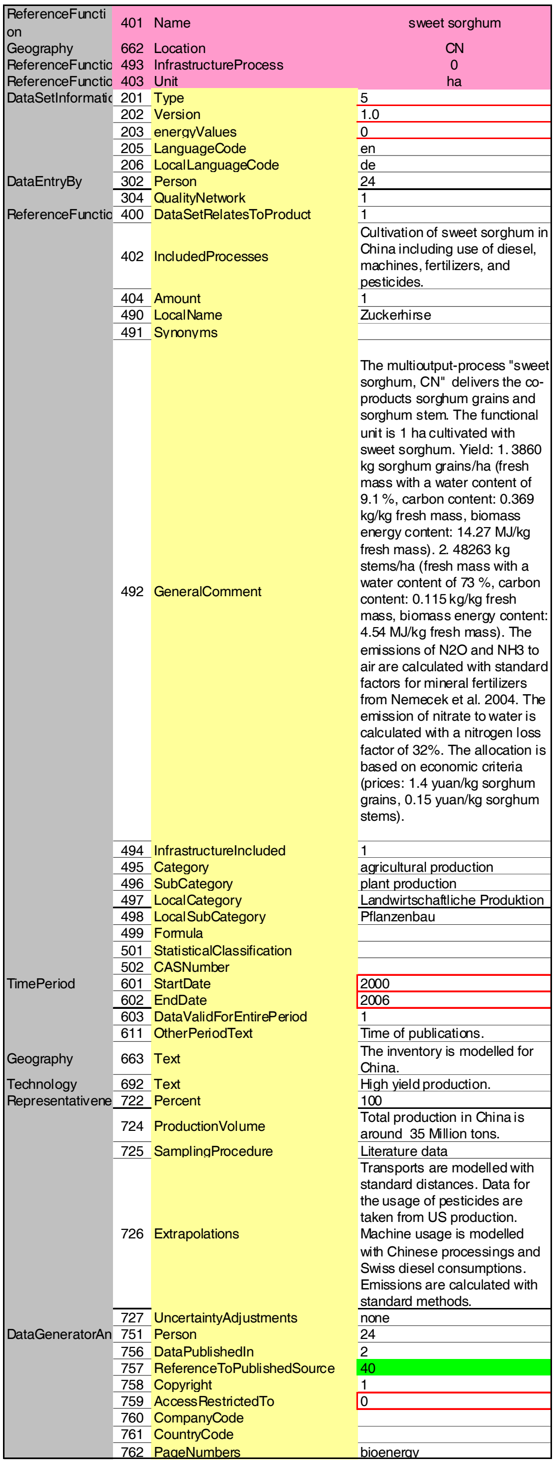
Tab. 11.22 Comparison of CED

	Sweet sorghum grains, at farm, CN	Sorghum grains (dos Santos 1997)	Sweet sorghum stems, at farm, CN	Sorghum stems (dos Santos 1997)
CED, non-renewable energy resources, (MJ-Eq)	3.2	1.2	0.3	0.13

11.13 Conclusions

The life cycle inventory for the sweet sorghum cultivation in China is determined largely by the machine and the fertilizer usages. For further work more information about machine usage and the consumption of fertilizers and pesticides in China should be included. The emissions of N2O, NOx and NH3 to air and of nitrate and phosphorus to water should be calculated with a better model.

Appendix: EcoSpold Meta Information



ReferenceFunction	401	Name	sweet sorghum
Geography	662	Location	CN
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	ha
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Cultivation of sweet sorghum in China including use of diesel, machines, fertilizers, and pesticides.
	404	Amount	1
	490	LocalName	Zuckerhirse
	491	Synonyms	
	492	GeneralComment	The multioutput-process "sweet sorghum, CN" delivers the co-products sorghum grains and sorghum stem. The functional unit is 1 ha cultivated with sweet sorghum. Yield: 1. 3860 kg sorghum grains/ha (fresh mass with a water content of 9.1 %, carbon content: 0.369 kg/kg fresh mass, biomass energy content: 14.27 MJ/kg fresh mass). 2. 48263 kg stems/ha (fresh mass with a water content of 73 %, carbon content: 0.115 kg/kg fresh mass, biomass energy content: 4.54 MJ/kg fresh mass). The emissions of N2O and NH3 to air are calculated with standard factors for mineral fertilizers from Nemecek et al. 2004. The emission of nitrate to water is calculated with a nitrogen loss factor of 32%. The allocation is based on economic criteria (prices: 1.4 yuan/kg sorghum grains, 0.15 yuan/kg sorghum stems).
	494	InfrastructureIncluded	1
	495	Category	agricultural production
	496	SubCategory	plant production
	497	LocalCategory	Landwirtschaftliche Produktion
	498	LocalSubCategory	Pflanzenbau
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled for China.
Technology	692	Text	High yield production.
Representativene	722	Percent	100
	724	ProductionVolume	Total production in China is around 35 Million tons.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Transports are modelled with standard distances. Data for the usage of pesticides are taken from US production. Machine usage is modelled with Chinese processings and Swiss diesel consumptions. Emissions are calculated with standard methods.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	bioenergy

References

BIOBIB 1996	K. Reisinger, C. Haslinger, M. Herger, H. Hofbauer: BIOBIB- a Database for Biofuels, THERMIE- Conference: Renewable Energy Databases, Harwell (United Kingdom), 1996
Dauriat 2000	Dauriat, Arnaud: Penetration potentialities of new ethanol production routes from lignocellulosic biomass. EPFL Lausanne 2000
Dauriat 2006	Dauriat, Arnaud: ENERS, Lausanne. Personal communication 2006

FAO 2002a	FAO 2002: Sweet Sorghum in China. In: World food submit five years later. Agriculture Departement FAO
FAO 2002b	FAO 2002: Fertilizer use by crop. Fith ed. Rome 2002
FAOSTAT 2006	Faostat Database Query: Sorghum Production. Retrieved 16. May 2006, from http://faostat.fao.org/faostat/
Frischknecht et al. 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
IFA 2006	IFA (2006): World Fertilizer Use Manual. Retrieved 16. May 2006, from http://www.fertilizer.org/ifa
KTBL 2004	Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V.: Betriebsplanung Landwirtschaft 2004/2005 – Daten für die Betriebsplanung in der Landwirtschaft. 20. Auflage. Darmstadt
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
dos Santos 1997	dos Santos, M.: Energy analysis of crops used for producing ethanol and CO2 emissions. Energy Planning Program/COPPE/UFRJ. Rio de Janeiro 1997
Smith et al. 2000	Smith, C. W., Frederiksen, R. A. (Ed.): Sorghum. Origin, History, Technology, and Production. Wiley Series in Crop Sciences. Wiley, New York 2000
USDA 2004	United States Department of Agriculture. National Agricultural Statistics Service: Agricultural Chemical Usage 2003. Field Crops Summary. May 2004

Part II

II.iii. Biomass conversion to fuels

Authors: see individual chapter

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12 Biogas

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Corrections for v2.1

The datasets for “biowaste, to anaerobic digestion” in Tab. 12.2 and Tab. 12.16 and for the “anaerobic digestion plant” in Tab. 12.21 have been corrected for ecoinvent data v2.1.

Summary

The present chapter deals with the life cycle inventories of biogas generation. The expression biogas as used in this section refers to gas derived from fermentation of various substrates such as: biowaste, sewage sludge, liquid manure, grass and whey as well as co-fermentation of liquid manure and biowaste. Biogas can be used a) as a feedstock for co-generation processes or b) after upgrading, it can be used as transportation fuel or feed in the natural gas network.

12.1 Introduction

Miscellaneous substrates may be used for the generation of biogas. In this study, life cycle inventory data and the underlying assumptions for biogas production are presented for the following substrates and processes:

- Fermentation of biowaste
- Fermentation of sewage sludge
- Fermentation of liquid manure
- Co-Fermentation of liquid manure and biowaste
- Fermentation of grass
- Fermentation of whey

In this project only one option for each digestion process has been modelled. However, various options and may be possible and reasonable, e.g. with respect to allocation approach and energy supply for the digestion process.

Here we have harmonized different allocation approaches in view of the ecoinvent guidelines for modelling of such processes. Nevertheless, these modelling assumptions are one viewpoint reflecting the economic and technical circumstances for the design of such processes.

The presented datasets in this research can be applied for specific case studies or specific research questions. However, the user of the data has to check, whether the assumptions made in this project are consistent with goals, scope and assumptions made in his study and may adjust the datasets if required.

12.1.1 External vs. Internal Use of Biogas

In principle the produced biogas can be used internally (on site) to cover heat (combustion of biogas, co-generation) and electricity (co-generation) demands of the digestion process or externally, e.g. it can be further upgraded to natural gas quality and fed into the natural gas network or used as a transportation fuel for natural gas vehicles.

Datasets – as presented in this study – are based on the assumption that biogas is upgraded and used as a transportation fuel. In such cases, processes most likely would be optimised in a way that the maximum yield of biogas is achieved. The reason for this is that a higher biogas throughput in the biogas upgrading plant significantly reduces the cost for the biogas upgrading. Thus, the required energy demand is obtained externally from conventional energy carriers. However, for digestion of manure and whey – characterised by a low biogas yield (see table Tab. 12.53) – we assume that upgrading is the less preferable option and the biogas is used internally for on-site heat and electricity supply.

Clearly, the user of the data has to check whether these assumptions are consistent with the goal, scope and assumptions of his study and may adjust the datasets. It should be noted, that an on-site use of biogas – e.g. in co-generation – would result in a lower process efficiency of the digestion process; i.e. different assumptions with respect to the final yield of biogas are required, because a part of the biogas is used internally.

12.1.2 System Boundaries and Allocation

In cases, where the substrate is exclusively used to produce biogas (manure, whey and sewage sludge) system boundaries are set in such a way that only those processes are modelled, which are required for the digestion of the substrate. Thus, allocation is avoided. In some cases, however, the substrate is used for the production of additional products (biowaste and grass). In such cases, we employ an allocation approach, where all products and services of the process are taken into account and all inputs and outputs to the process are modelled as observed in practice.

The production of the substrate is only considered for grass-digestion. In all other cases, the substrate (manure, whey, sewage sludge and biowaste) is considered as a waste product and hence no environmental burdens are accounted for. However, transport expenditures of the substrate – if not generated on-site – are accounted for.

12.2 Reserves and Resources

Information about the development and current state of the biogas production is available from the Swiss statistic of renewable energies (BFE 2003), part biogas. In principle a distinction is made between the following sectors:

- agricultural biogas generation,
- industrial wastewater biogas generation,
- biowaste biogas generation,
- co-fermentation of raw sludge and biowaste in waste water treatment plants.

In Tab. 12.1 the current state (2002) of the biogas production in Switzerland and the use of biogas are documented.

Tab. 12.1 Biogas production in Switzerland and the use of biogas (figures representing the situation in the year 2002, resp. 2006)

	Unit	Agriculture		Industrial wastewater	Biowaste	Co-fermentation of raw sludge 1)	Total
		2002	2006				
Plants	No.	63		20	13	56	152.0
Gross biogas production	GWh_{Biogas}/a	19.50	79.8	33.65	43.97	47	144.1
Used heat	GWh_{th}/a	3.46	29.1	19.99	6.41	n.a.	29.6
Electricity production	GWh_{el}/a	4.49	25.0	2.19	9.8	10.34	26.8
Unused heat	GWh_{th}/a	1.25	25.7	1.85	6.08	n.a.	9.2
Vehicle fuel	GWh_{fuel}/a	0	0	0	6.64	0	6.6
Share utilised gross biogas	%	47.2	68	71.4	65.8	22.0	50.3

1: the biogas production based on co-fermentation is about 10% of the total sewage gas production of waste water plants in Switzerland.

According to Tab. 12.1 biowaste fermentation and co-fermentation of raw sludge currently are the major sources for biogas production and electricity generation. The high share of electricity production results in a high share of unused heat, since the use of biogas in co-generation units leads to a high heat production, for which no further use is available at most sites. In the year 2002, a further upgrade of biogas to vehicle fuel was exclusively performed at biowaste fermentation sites. However, in 2004 the first waste water treatment plant was equipped with a biogas upgrading unit (WWTP Buholz).

It should be noted, that merely 10% of the sewage gas production is derived from co-fermentation of raw sludge and biowaste. Seen in this light, the gas-production from raw sludge in waste water treatment plants is considerably higher than the production of gas from any other substrate.

In 2000 over 95% of the Swiss population were connected to a municipal wastewater treatment plant (WWTP) generating 1'441 million m^3 of wastewater in 2900 municipalities.

WTTP capacities are expressed in per-capita equivalents PCE. One PCE equates to a load of 60 grams of BOD in raw sewage per day, which is the typical BOD load generated by one person. Swiss WWTPs treated 1441.5 million m3 wastewater in 2000 (BUWAL 2001b) from 7'135'718 inhabitants, resulting in an annual amount of 202 m3 of wastewater per PCE (Doka 2003).

In total, 888 WWTP are in operation out of which 624 performed anaerobic stabilisation. The Swiss WWTP are grouped into different capacity classes (German 'Grössenklassen'). The majority of plants are small scale plants (class 4 and 5) for annual treatment of 10'000 PCE or less. However in these small plants only a minority of the Swiss wastewater is treated. Over 90% of the wastewater is treated in large plants (classes 1, 2 and 3 with an annual treatment of >100’000, 50’000 -100’000 and 10’000 – 50’000 PCEs, respectively). It is also in these plants, where anaerobic stabilisation is the dominating stabilisation treatment. 243 plants are equipped with a cogeneration unit.

12.3 Characterisation of the Product

The quantity (degradation rate) and quality of the biogas depend on several factors:

- composition of the input material (share of dry organic matter)
- duration of digestion
- temperature inside digestion tank
- quality and quantity of co-substrates

12.3.1 Biogas from Biowaste

The properties of the biogas vary as a function of plant design and waste composition. The waste composition in this project represents composition of biowaste in the Swiss Canton of Zurich. The data is available from Schleiss (1999) and is summarised in Tab. 12.2. For several elements the data is derived from detailed analysis of compost in the canton of Zürich (AWEL 1998). The data have been harmonized with the data for incinerated biowaste in Tab. 22.2.

Tab. 12.2 Elementary Composition of Biowaste

Water Content	60%	Arsenic	0.0002%	Tin	0.0008%
Oxygen	12.64%	Cadmium	0.00001%	Vanadium	0.0003%
Hydrogen	2%	Cobalt	0.0005%	Zinc	0.00582%
Carbon (tot.)	16,24%	Chromium	0.0008%	Silicon	3.998%
Sulphur	0.15%	Copper	0.0018%	Iron	0.06%
Nitrogen	0.4%	Mercury	0.00001%	Calcium	2.18%
Phosphor	0.11%	Manganese	0.00043%	Aluminium	0.9995%
Boron	0.001%	Molybdenum	0.00004%	Potassium	0.35%
Chlorine 1)	0.4%	Nickel	0.00054%	Magnesium	0.282%
Fluorine	0.02%	Lead	0.00186%	Sodium	0.15%
Bromine	0.0006%	Iodine	0.00001%	Selenium	0.00005%

1: data based on oral communication with Konrad Schleiss May, 2005

According to Tab. 12.2 we assume for further calculations a share of dry matter of 40%.

The heating value of biogas varies based on the volumetric percentages of component gases. In Tab. 12.3 the volumetric composition of biogas as reported in the literature and the figures employed in this project are summarised. Densities and heating values of the produced biogas are calculated according to the below equation. Required density and heating values of single components are presented in Tab. 12.4.

$$HV_{Biogas} = HV_{CH_4} * v_{CH_4} + HV_{H_2S} * v_{H_2S}$$

Tab. 12.3 Volumetric composition, density and heating values of biogas generated from biowaste

Composition of Biogas	Unit	Schleiss 1)	Rütgers min CH_4 2)	Rütgers max CH_4 3)	This project
CH_4 (v_{CH4})		67.00%	55.00%	70.00%	67.00%
CO_2 (v_{CO2})		32.30%	43.75%	28.75%	32.05%
N_2 (v_{N2})		0.70%	1.00%	1.00%	0.70%
H_2S (v_{H2S})			0.00050%	0.00050%	0.00050%
O_2 (vO_2)			0.25%	0.25%	0.25%
Density (kg/Nm$_3$)	kg/Nm^3	1.122	1.268	1.081	1.120
Lower Heating Value (LHV)	MJ/Nm^3	24.043	19.737	25.120	24.043
Higher Heating Value (HHV)	MJ/Nm3	26.622	21.854	27.815	26.622

1: Values are derived from Schleiss (2000).

2: Minimum Value for CH_4 and maximum for CO_2.

3: Maximum Value for CH_4 and minimum for CO_2.

Tab. 12.4 Densities and heating values for gas components

Component	**Density (normal conditions) ρ**		**Lower Heating Value (LHV)**	**Upper Heating Value (UHV)**
		kg/m^3	MJ/Nm^3	MJ/Nm^3
Methane	$\rho_{CH4,273K}$	0.714	35.885	39.735
Carbon Dioxide	$\rho_{CO2,273K}$	1.964	0	0
Nitrogen	$\rho_{CN2,273K}$	1.254	0	0
Hydrogen Sulfide	$\rho_{H2S,273K}$	1.517	23.413	n.a.
Oxygen	$\rho_{O2,273K}$	1.428	0	0

12.3.2 Biogas from Sewage Sludge

In Tab. 12.5 the properties of biogas generated from sewage sludge as applied in this project are summarised.

Tab. 12.5 Composition of biogas from sewage sludge and referring heating values. (Data of composition are derived from Ronchetti et al. (2002), density and heating values based on own calculations.)

Composition of Sewage Gas	**Unit**	
Carbon dioxide	v_{CO2}	33.60%
Methane	v_{CH4}	63.00%
Nitrogen	v_{N2}	3.40%
Density	kg/Nm^3	1.152
Lower Heating Value (LHV)	MJ/Nm^3	22.608
Upper Heating Vaule (UHV)	MJ/Nm^3	25.033

12.3.3 Biogas from Liquid Manure

For biogas from liquid manure we assume the same properties and characteristics as for biogas from biowaste. In Tab. 12.3 the properties of biogas generated from biowaste are summarised.

12.3.4 Biogas from Grass

In Tab. 12.6 the properties of biogas generated from grass and grass-silage as applied in this project are summarised. The relatively high share of CO_2 in the generated biogas is a consequence of feeding the biogas with emissions of the gasholder. These emissions are characterised by a high share of CO_2 (Baier & Delavy 2003).

Tab. 12.6 Composition and heating values of biogas derived from the digestion of grass juice. (Data of composition are derived from Baier & Delavy (2003), density and heating values based on own calculations.)

Component	**Unit**	
Methane	Vol %	55
Carbon Dioxide	Vol %	45
Hydrogen Sulfide	ppm	80
Density	kg/Nm3	1.28
Lower Heating Value	MJ/Nm3	19.74
Upper heating Value	MJ/Nm3	21.85

12.3.5 Biogas from Whey

In Tab. 12.7 the properties of biogas generated from whey as applied in this project are summarised.

Tab. 12.7 Composition and heating values of biogas from digestion of whey. (Data of composition are based on additional information of Fruteau de Laclos & Membrez 2004, available from Arnaud Dauriat (ENERS), density and heating values based on own calculations.)

Component	**Unit**	
Methane	Vol %	50.0
Carbon Dioxide	Vol %	50.0
Density	kg/Nm3	1.34
Lower Heating Value	MJ/Nm3	17.94
Upper heating Value	MJ/Nm3	19.87

12.3.6 Summary of Properties of Biogas

In the below table the main properties of the produced biogas from the considered substrates are summarised.

Tab. 12.8 Summary of main properties of biogas from various substrates as used in this project

		Biowaste	**Raw Sewage Sludge**	**Liquid manure**	**Grass**	**Whey**
Methane	Vol. %	67.00	63.00	67.00	55.00	50.00
Carbon Dioxide	Vol. %	32.05	33.60	32.05	45.00	50.00
Methane	Kg/Nm^3	0.47857	0.45000	0.47857	0.39286	0.35714
Carbon Dioxide	Kg/Nm^3	0.62930	0.65974	0.62930	0.88358	0.98175
Total Carbon Content	Kg/Nm^3	0.53056	0.51743	0.53056	0.53562	0.53561
Nitrogen	Vol. %	0.70000	3.40000	0.70000	-	-
Density	Kg/Nm^3	1.12	1.15	1.12	1.28	1.34
Lower Heating Value	MJ/Nm^3	24.04	22.61	24.04	19.74	17.94

12.4 Use of the Product

Biogas obtained in the fermentation process can be generally used in various ways:

- use as a fuel for heating (combustion in boilers)
- use as a fuel in co-generation systems: biogas is transformed into electrical power and thermal energy, ensuring autonomous operation with a considerable energy surplus.
- fed into the natural gas network (biogas is upgraded to natural gas quality).
- use as a vehicle fuel (biogas is upgraded to natural gas quality and then used as a fuel for road vehicles).

The produced amount of fuel is sufficient for the operation of 910 cars with an average petrol consumption of 8l/100km and a yearly kilometric performance of 10’000 km (BFE 2003).

12.4.1 Biogas from Biowaste

In Tab. 12.9 the development of the biogas production from household biowaste and the use of biogas are documented.

Tab. 12.9 Production and use of biogas products from 1992 – 2002 (BFE 2003)

	Unit	1992	1996	2000	2002
Plants	No.	1	6	11	13
Gross biogas production	GWh_{Biogas}/a	1.9	11.8	30.8	43.9
Heat for digestion tank	GWh_{th}/a	0.14	0.88	2.04	2.94
Used heat	GWh_{th}/a	0.3	1.55	5.23	6.41
Electricity consumption	GWh_{el}/a	0.5	3.24	6.7	9.80
Vehicle fuel	GWh_{fuel}/a	0	0.55	5.23	6.64

In 2002 biogas based fuels were available at three petrol stations. In addition 10 petrol stations offer so called “Naturgas”, a mix of biogas and fossil natural gas.

12.4.2 Sewage Gas

Sewage gas is well suited as a fuel for co-generation. The obtained heat is sufficient to cover the overall heat consumption of a WWTP, including the heat demand for the fermentation process. Furthermore, sewage gas may be directly burnt for heating purposes. In principle, the generated sewage gas can be upgraded to natural gas quality and then used as a fuel for road vehicles or fed into the natural gas network. In the year 2004 the waste water treatment plant Buholz was equipped with a biogas upgrading plant.

12.4.3 Biogas from Agriculture Fermentation Plants

For Switzerland two types of fermentation plants with respect to the final use of the biogas can be distinguished:

- plants equipped with a co-generation unit producing heat and electricity and
- plants with boilers using the gained biogas only for heating.

In recent years, the number of plants with exclusively utilisation of the biogas for heating has decreased, while the number of plants equipped with co-generation units has increased. The total number of plants remained the same, since small plants has been replaced by bigger ones.

In Tab. 12.10 the development of the biogas production in agriculture plants are documented.

Tab. 12.10 Production figures of biogas in agriculture plants from 1992 – 2002 (BFE 2003)

	Unit	1998	2000	2002
Plants	No.	63	62	63
Gross biogas production	GWh_{Biogas}/a	12.57	16.08	19.49
Used heat	GWh_{th}/a	3.10	3.18	3.46
Electricity production	GWh_{el}/a	2.07	3.17	4.49
Unused heat	GWh_{th}/a	0.97	1.11	1.25

According to BFE (2003), biogas plants with co-fermentation; i.e. joint digestion of liquid manure and biowaste, have increased their production in recent years.

12.4.4 Biogas from Grass

A first biorefinery started operation in 2001 in Schaffhausen, Switzerland. The plant produced technical fibres and biogas, and had a throughput capacity of around 0.8 tonnes of dry matter per hour. However, the Schaffhausen installation was not economically viable and operation ceased in summer 2003. The biogas generated during the test operation has been used as a fuel for co-generation (Baier & Delavy 2003).

12.4.5 Biogas from Whey

Switzerland produces 160'000 tons of cheese per year, resulting in the production of 1.5 millions m^3 cheese whey. This waste product has a high energetic value and has been used up to now for pigs feeding, an utilisation that encounters more and more constraints. Alternative ways to recover the valuable resources of cheese whey are the production of renewable energy by producing biogas or bio-ethanol. In this study LCI data for the production of biogas from whey is presented. Fruteau de Laclos & Membrez (2004) assumed that the biogas is used to generate heat for the digestion process as well as for the cheese production.

12.5 Biogas from Biowaste

12.5.1 System Characteristics

In Fig. 12.1 a schematic process flow sheet for biogas generation from biowaste and its usage and co-products is presented.

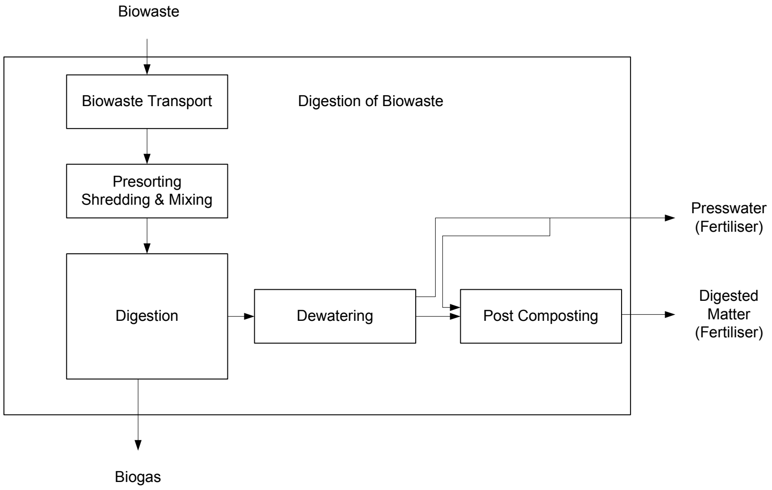

Fig. 12.1 Schematic process flow sheet for anaerobic digestion of biowaste

As illustrated in Fig. 12.1, transport expenditures for the delivery of the biowaste are inside the system boundaries.

The CO_2-fixation in the biowaste is accounted for as consumption of CO_2 as a resource. The actual value is based on the assumed biowaste composition (see Tab. 12.11).

Tab. 12.11 Characteristics of the biowaste composition and parameters of the digestion process

Biowast-Input	**t**	**1**
dry matter	%	40
organic share in dry matter	%	77
carbon content of organic matter	%	53

Data of the plant infrastructure is recorded in a separate unit process. Data of the co-generation and upgrading of biogas is addressed in the chapter "Use and Upgrading of Biogas".

12.5.2 Life Cycle Inventory of Biowaste Fermentation Plant

The data employed in this project represent a fermentation plant designed for processing 10'000 tonnes of biowaste per year.

Land use

KOMPOGAS (2005) reported a land use of c.a. 5000 m^2 for a plant with a capacity of 20'000 tonnes. In this study assuming a yearly capacity of 10'000 tonnes biowaste, we assume a land occupation of 3000 m^2.

For the original land type of biowaste plants no general information is available. Thus, we assume a transformation from unknown. The area occupied by the plant is inventoried as "built-up industrial". The plant operation time is assumed to be 25 years. During the construction time of one year the total area is inventoried as 'construction site'.

Construction expenditures

The fermentation tank consists of unalloyed steel (reinforcing steel). Stationary machines are accounted for as cast iron. Quantities of construction expenditures as used in this study are available from Schleiss (1999). In Tab. 12.12 the life cycle inventory data of the infrastructure expenditures for an anaerobic treatment of biowaste are summarised.

Tab. 12.12 Unit process raw data of biowaste fermentation plant.

	401	InputGroup	OutputGroup	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	anaerobic digestion plant, biowaste	UncertaintyType	StandardDeviation95%	GeneralComment
	662			Location						CH			
	493			InfrastructureProcess						1			
	403			Unit						unit			
product		-	0	anaerobic digestion plant, biowaste	CH	-	-	1	unit	1.00E+0			
technosphere		5		concrete, normal, at plant	CH	-	-	0	m3	1.85E+3	1	1.26	(3,4,2,1,1,5); literature studies
		5		reinforcing steel, at plant	RER	-	-	0	kg	1.20E+5	1	1.26	(3,4,2,1,1,5); literature studies
		5		aluminium, production mix, at plant	RER	-	-	0	kg	1.00E+3	1	1.26	(3,4,2,1,1,5); literature studies
		5		polystyrene, high impact, HIPS, at plant	RER	-	-	0	kg	3.92E+3	1	1.26	(3,4,2,1,1,5); literature studies
		5		polyvinylchloride, at regional storage	RER	-	-	0	kg	3.50E+3	1	1.26	(3,4,2,1,1,5); literature studies
		5		sand, at mine	CH	-	-	0	kg	1.06E+5	1	1.26	(3,4,2,1,1,5); literature studies
		5		gravel, round, at mine	CH	-	-	0	kg	1.97E+6	1	1.26	(3,4,2,1,1,5); literature studies
		5		bitumen, at refinery	CH	-	-	0	kg	1.12E+4	1	1.26	(3,4,2,1,1,5); literature studies
		5		cast iron, at plant	RER	-	-	0	kg	1.88E+5	1	1.26	(3,4,2,1,1,5); literature studies
		5		copper, at regional storage	RER	-	-	0	kg	3.00E+3	1	1.26	(3,4,2,1,1,5); literature studies
transport		5		transport, lorry 28t	CH	-	-	0	tkm	1.39E+5	1	2.09	(4,5,na,na,na,na); standard distances for used materials
		5		transport, freight, rail	CH	-	-	0	tkm	1.94E+5	1	2.09	(4,5,na,na,na,na); standard distances for used materials
disposal		5		disposal, building, reinforced concrete, to final disposal	CH	-	-	0	kg	4.08E+6	1	1.26	(3,4,2,1,1,5); literature studies
		5		disposal, asphalt, 0.1% water, to sanitary landfill	CH	-	-	0	kg	1.18E+5	1	1.26	(3,4,2,1,1,5); literature studies
		5		disposal, polystyrene, 0.2% water, to municipal incineration	CH	-	-	0	kg	3.92E+3	1	1.26	(3,4,2,1,1,5); literature studies
		5		disposal, polyvinylchloride, 0.2% water, to municipal incineration	CH	-	-	0	kg	3.50E+3	1	1.26	(3,4,2,1,1,5); literature studies
resource, land		4	-	Occupation, industrial area, built up	-	resour	land	-	m2a	7.50E+4	1	1.58	(2,4,2,1,1,5); literature studies
		4	-	Occupation, construction site	-	resour	land	-	m2a	3.00E+3	1	1.58	(2,4,2,1,1,5); literature studies
		4	-	Transformation, from unknown	-	resour	land	-	m2	3.00E+3	1	2.07	(2,4,2,1,1,5); literature studies
		4	-	Transformation, to industrial area, built up	-	resour	land	-	m2	3.00E+3	1	2.07	(2,4,2,1,1,5); literature studies

12.5.3 Life Cycle Inventory of Anaerobic Digestion of Biowaste

Technical characteristics

The delivered waste first undergoes a pre-treatment process (shredding and size separation). At this stage about 1% of contaminants are separated and inventoried as household waste for incineration. The remaining material is then mixed with process water and already fermented material in a mixer. Passing via heat exchangers, the substrate is pumped to a horizontal fermenter. The fermentation process inside the fermenter is based on anaerobic thermophile dry fermentation at a temperature of about 55 °C. The retention time in the fermenter is about 14 days (KOMPOGAS 2005). During the fermentation process biogas is produced. Water is then removed mechanically from the fermented material. The removed water is partly used as fertilizer in agriculture and for watering the post-composting. In addition, the digested matter is used as a mineral fertilizer in agriculture. In 2003, a production of 19'696 t presswater is reported for the digestion plants in the canton Zürich (Schleiss 2004). According to Ziegler (2004) a similar amount of digested matter is available as fertilizer. Both products are assumed to be used as a fertilizer in agriculture. The biogas generation is assumed to be 0.1 $Nm^3/kg_{Biowaste}$. Figures available from KOMPOGAS (2005) indicate a slightly higher biogas generation: 0.105 $Nm^3/kg_{Biowaste}$.Vogt et al. (2002) stated a value of 0.38 $m^3/kg_{organic\ dry\ matter}$.

Raw material input, transport and carbon balance

According to Schleiss (2004), 79'691 t of the total treated biowaste (136'473 t) in the canton Zürich are collected via municipal waste collection schemes. The remaining biowaste is directly delivered by private or commercial customers. In line with Schleiss (2000), transport expenditures for biowaste delivered by private or commercial customers are not accounted for in this study. In case of household biowaste, municipal collection of the waste with special waste collection vehicles usually applies. Life Cycle inventories for municipal collection are available from Doka (2003) and employed in this study. According to Vogt (2002), we assume a distance of 15 km. Moreover, Vogt (2002) reported an addition transport (17 km) of biowaste from municipal collection points to the actual biowaste plant. For this transport we assume a 28 t lorry, as available from Spielmann (2004). The fixation of carbon dioxide in the biowaste is accounted for with 0.595 $kg_{CO2}/kg_{biowaste}$. The inventory input data is summarised in Tab. 12.16.

Energy consumption

Energy Consumption figures are available from various sources and summarised in Tab. 12.13. In principle various concepts of energy supply are possible. If the biogas is used as a fuel for cogeneration, energy expenditures may be covered by the produced heat and electricity from on-site cogeneration. However, this would result in a lower process efficiency of the digestion process; i.e. different assumptions with respect to the final yield of biogas are required. On the other hand, if biogas is assumed to be used as a feedstock for transportation fuels, the process most likely would be optimised in a way that the maximum yield of biogas is achieved. The reason for this is that a higher biogas throughput in the biogas upgrading plant significantly reduces the cost for the biogas upgrading[22]. In case that all biogas is fed in the upgrading plant, the required heat and electricity is obtained from conventional energy carriers.

The dataset as presented in this study, is based on the assumption, that the biogas is upgraded and used as a fuel. For electricity the current Swiss supply mix is employed. For heat supply various options are possible. In this study we assume that the heat demand is covered by natural gas combustion. Alternatively also wood chips may be used.

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[22] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

Tab. 12.13 Energy Consumption for biowaste fermentation (thermophile dry fermentation)

	Unit	Plant in Germany [1]	Plant in Switzerland [2]	Average for all plants in Canton Zürich[4]	Plant in Switzerland 1990ties. [5]	This project [6]
Electricity	kWh/t Input Biowaste	80	29	55	67	40
Heat	MJ/t Biowaste	324	594 [3]	468	-	594

1: Values are representative for the total plant (Vogt et al. 2002)

2: KOMPOGAS 2005

3: Values exclusively for heating of the digestion tank

4: Schleiss 2004: the electricity value also includes the consumption of electricity for gas purification

5: Schleiss & Edelmann 2000

6: oral communication Konrad Schleiss May 2005: Assumptions: 30 kWh for pre-treatment and 10 kWh for dewatering

In the last column the data as used in this project is summarized. In addition we account for a diesel consumption of 18 MJ/t biowaste for the operation of a forklift in post-composting.

Emissions to air

Methane-emissions (CH_4) and CO_2-emissions exclusively occur after digestion during aerobic post-treatment of digested matter. Emissions due to leakage of pipes are not reported and thus are neglected.

In this project we assume a total biological decomposition of 55% of the organic matter in the biowaste. We further assumed that 76% of the decomposition takes place during the anaerobic treatment, and hence 24% of the decomposition will occur in the aerobic post treatment of digested matter (Schleiss & Edelmann 2000). In digestion plants there is a considerable potential of methane emission during the "aerobic" post-treatment, even if just a small percentage of the organic breakdown takes place outside the digester. Edelmann (2004) claims that high methane emissions are caused by the intensive inoculation of the dewatered solid output with anaerobic bacteria. However, methane emissions occur even in pure composts, which are reversed very often. According to Konrad Schleiss (oral communication) these results should be interpreted carefully, since they are based on a relatively low number of measurements, which have been performed in the initial phase of post-composting.

Due to a lack of further information we employ the data available from Schleiss & Edelmann 2000 and assume a share of methane-carbon of about 30%. In Tab. 12.14 the resulting CO_2- and CH_4-emissions and the underlying assumption are summarised.

Tab. 12.14 CO_2- and CH_4-emissions and the underlying assumption

Biowast-Input	**t**	**1**
dry matter	%	40
organic share in dry matter	%	77
carbon content of organic matter	%	53
share of carbon decomposition during digestion		0.76
share of carbon decomposition during post-composting		0.24
total organic decomposition		0.55
carbon composition during composition	kg/t	67.97
carbon decomposition during post-composting	kg/t	21.46
share of methane-C from post composting		0.30
methane-C due to post composting	kg/t	6.40
methane emissions (CH4)	kg/t	8.53
carbon dioxide - C due to post composting	kg/t	15.07
carbon dioxide emissions	kg/t	55.25

Gronauer et al. (1997) stated that about 12% of the total nitrogen leak in form of ammonia. The emission of ammonia can be reduced by 95%, if a biofilter is in operation. In this project we assume that a biofilter is installed. It should be noted that we merely account for the effect of the biofilter in operation but not for expenditures due to the operation and installation itself. In contrast to ammonia, dinitrogen monoxide cannot be restrained with a biofilter. Data of dinitrogen monoxide as well as for hydrogen sulfide emissions is available from Gronauer et al. (1997). For the latter, Gronauer et al. (1997) claim an emission of 700 g per tonne input dry matter. Thus, assuming a share of dry matter of 40%, we obtain an emission of hydrogen sulphide of 2852 kg H_2S per 10.000 t of biowaste. One question so far remains unanswered: what happens with the NO_3 in the biofilter. Under suboptimal circumstances, the biofilter may become a N_2O generator.

Additional ammonium emissions, occurring when presswater is spread on agriculture land, are accounted for with 0.625 kg/m^3 presswater.

Emissions to soil

Emissions to soil occur when digested matter and presswater are used as fertilizer in agriculture. The actual emission score is derived from the composition of the biowaste.

Allocation

The principle question with respect to allocation of emissions in the biogas generation process is, whether the biogas generation is considered as a waste treatment process, or as a “production” process. Currently, separate treatment of biogas is motivated by cost reduction and waste management policies. Furthermore, as stated above, the digestion process yields two additional products: press water and digested matter, which are used as a fertiliser in agriculture.

In this study, we assume that biowaste treatment fulfils three functions:

- Disposal of biowaste,
- production of biogas,
- production and use of presswater and digested matter as fertiliser in agriculture

Consequently, the generation of biogas from biogas is modelled in a multi-output process.

The allocation is based on economic figures; i.e. the revenues of a plant with a yearly treatment capacity of 10’000 tonnes of biowaste. According to BFE (2004) the revenue for biowaste treatment in the canton Zurich varies from 120 – 160 CHF/tonne. In line with the latter study we assume a revenue of 126 CHF/tonne. Figures for the revenue of biogas are not readily available. The German “Fachverband

Bioenergie" suggested a compensation of 5-10 cents/kWh for the feeding of biogas in the gas or electricity network (IWR 2001). Mr. Zeifang from KOMPOGAS reported a quantity of 0.04 CHF/kWh[23]. The later value is used in this study. Presswater and digested matter are usually given to the farmers free of charge. Consequently, for the production of presswater and digested matter no environmental burdens are accounted for. On the other hand, emissions that occur during the application and use of fertilisers in agriculture are merely allocated between the application of presswater and digested matter as a fertiliser and the disposal of biowaste. In this study, we pursued a practical approach and allocated 50% of the environmental exchanges occurring in the use of the presswater and digested matter to the production of fertiliser and 50% to the disposal service of biowaste.

Tab. 12.15 Allocation figures for biowaste treatment (excluding the application of digested matter and presswater in agriculture.

Function	Revenue	Unit	Quantity	Unit	Total revenue	Allocation Key	Comment
Disposal of biowaste	126	CHF/t	10000	t/a	1260000	0.82	quantity available from (KOMPOGAS, 2005) and oral
Production of biogas	0.04	CHF/KWh	1054000	Nm3/a	281067	0.18	communication with Mr. Zeifang, KOMPOGAS (12.04.2006)
Production of fertilser	0	CHF/kg	-			0	

For CO_2-emissions a different allocation rule is applied. The employed allocation factors are based on the carbon balance and adjusted in such a way that the carbon balance is valid for the entire process as well as for each single product.

In Tab. 12.16 the input data of the biowaste treatment multi-output process is presented.

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[23] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

Tab. 12.16 Unit process raw data of anaerobic digestion of bio waste

Explanations	Name	Location	Infrastructure-Process	Unit	biowaste, to anaerobic digestion	uncertaintyType	StandardDeviation95%	GeneralComment	biogas, from biowaste, at storage	disposal, biowaste, to anaerobic digestion	digested matter, application in agriculture
	Location				CH				CH	CH	CH
	InfrastructureProcess				0				-	-	-
	Unit				kg				Nm3	kg	kg
Technosphere	heat, natural gas, at boiler condensing modulating >100kW	RER	0	MJ	5.94E-1	1	1.23	(2,3,2,3,1,5); literature studies and oral communication	18.24	81.76	-
	electricity, low voltage, at grid	CH	0	kWh	4.00E-2	1	1.23	(2,3,2,3,1,5); literature studies and oral communication	18.24	81.76	-
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	1.00E-2	1	1.25	(3,3,2,3,1,5); literature studies	18.24	81.76	-
	anaerobic digestion plant, biowaste	CH	1	unit	4.00E-9	1	3.07	(3,3,2,3,1,5); literature studies	18.24	81.76	-
	transport, municipal waste collection, lorry 21t	CH	0	tkm	8.76E-3	1	1.26	(3,4,2,3,1,5); literature studies	18.24	81.76	-
	transport, lorry 20-28t, fleet average	CH	0	tkm	9.92E-3	1	2.08	(3,4,2,3,1,5); literature studies	18.24	81.76	-
	diesel, burned in building machine	GLO	0	MJ	1.80E-2	1	1.23	(2,3,2,3,1,5); Diesel is used for operation of forklifts in post composting.	-	-	100.00
	transport, lorry 3.5-20t, fleet average	CH	0	tkm	1.50E-2	1	2.10	(4,5,na,na,na,na); standard transport distance for compost	-	50.00	50.00
	solid manure loading and spreading, by hydraulic loader and spreader	CH	0	kg	1.00E+0	1	1.25	(3,3,2,3,1,5); own assumption	-	50.00	50.00
resource, in air	Carbon dioxide, in air			kg	5.95E-1	1	1.29	(3,4,3,3,1,5); own calculation based on literature studies	55.00	-	45.00
air, unspecified	Carbon dioxide, biogenic			kg	7.05E-1	1	1.29	(1,3,3,3,1,5); literature studies	18.26	81.79	- 0.05
	Methane, biogenic			kg	8.53E-3	1	3.11	(3,3,4,3,1,5); literature studies	18.24	81.76	-
	Dinitrogen monoxide			kg	9.98E-5	1	1.63	(2,3,4,3,1,5); literature studies	18.24	81.76	-
	Ammonia			kg	3.19E-4	1	1.39	(2,3,4,3,1,5); literature studies	13.08	72.77	14.15
	Hydrogen sulfide			kg	2.45E-4	1	1.63	(2,3,4,3,1,5); literature studies	18.24	81.76	-
	Heat, waste			MJ	1.44E-1	1	3.06	(2,3,2,3,1,5); literature studies	18.24	81.76	-
soil, agricultural	Phosphorus			kg	1.13E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Boron	-	-	kg	1.02E-5	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Chloride	-	-	kg	4.00E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Bromine	-	-	kg	6.00E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Fluoride	-	-	kg	2.00E-4	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Arsenic	-	-	kg	2.00E-6	1	1.60	(3,3,3,3,1,5); literature studies and oral communication	-	50.00	50.00
	Cadmium	-	-	kg	1.38E-7	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Cobalt	-	-	kg	5.00E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Chromium	-	-	kg	8.00E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Copper	-	-	kg	1.80E-5	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Iodide	-	-	kg	5.50E-8	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Mercury	-	-	kg	7.00E-8	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Manganese	-	-	kg	4.30E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Molybdenum	-	-	kg	4.00E-7	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Nickel	-	-	kg	5.42E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Nitrogen	-	-	kg	3.68E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Lead	-	-	kg	1.86E-5	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Selenium	-	-	kg	5.00E-7	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Sulfur	-	-	kg	1.50E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Tin	-	-	kg	8.00E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Vanadium	-	-	kg	3.00E-6	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Zinc	-	-	kg	5.82E-5	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Silicon	-	-	kg	4.00E-2	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Iron	-	-	kg	6.00E-4	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Calcium	-	-	kg	2.18E-2	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Aluminum	-	-	kg	1.00E-2	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Potassium	-	-	kg	3.50E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Magnesium	-	-	kg	2.82E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
	Sodium	-	-	kg	1.50E-3	1	1.60	(3,3,3,3,1,5); literature studies	-	50.00	50.00
Outputs	biogas, from biowaste, at storage	CH	0	Nm3	1.00E-1				100.00		
	disposal, biowaste, to anaerobic digestion	CH	0	kg	1.00E+0					100.00	
	digested matter, application in agriculture	CH	0	kg	7.12E-1						100.00

Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

12.6 Biogas from Raw Sludge in Waste Water Treatment Plants

12.6.1 System Characteristics

The functional unit is the production of one cubic metre of biogas from raw sludge. The system boundary is selected accordingly; i.e. only the environmental burden due to the installation (digestion tank and gasholder) and operation of the anaerobic treatment of sewage sludge are taken into account. The actual pre-treatment of wastewater producing the raw sludge as well as the subsequent treatment of the digested sludge is not included in this study. Thus, all environmental burdens of pre-treatment and subsequent treatment of digested sludge are allocated to the waste treatment, and not accounted for in the production of sewage gas. This approach is in line with the zero-allocation for biogas in the multi-output process of biowaste treatment, applied with respect to the further treatment and use of digested matter and presswater. Data of plant infrastructure are recorded in a separate unit process.

12.6.2 Life Cycle Inventories of Sewage Sludge Fermentation Facilities

In Doka (2003) the infrastructure for entire waste water treatment plants are described. In this study only the facilities required for the anaerobic treatment of sewage sludge are taken into account, including digestion tank and gasholder. Life cycle inventory data of infrastructure expenditures and land use for these facilities is available from Ronchetti (2002).

Land use

Sewage plants are usually located near a river and are erected on formerly open, unsealed land. In line with Doka (2003) the original land type 'pasture and meadow' is assumed ("transformation from"). Construction time is assumed to be 3 years (assuming that digestion of sludge is predominately performed on large wastewater treatment plants (Ronchetti et al. 2002). During the construction time the total area is inventoried as 'construction site'. Land transformations to and from construction sites are not inventoried in ecoinvent 2000, but their land occupation is (Frischknecht et al. 2003a). The area occupied by the digestion tank and gasholder is inventoried as 'built-up industrial' (sealed). The plant operation time is assumed to be 30 years. After that time the plant is expanded, renovated or closed down.

Ronchetti (2002) provided land use figures for the surface covered by digestion tank and gasholder (see Tab. 12.17). In this study we assume a plant of 100'00 PCEs (upper limit class 2)

Tab. 12.17 Technical Characteristics for digestion tank and gasholder

	Unit	100'000 PCE	50'000 PCE	10'000 PCE
Area	m^2	1140	600	130
Volume digestion tank (2 vessels)	m^3	2700	1400	300
Volume gasholder	m^3	4000	2100	450

Construction expenditures

Digestion tanks normally consist of a concrete vessel covered with concrete roof structures of different shape and structural design. The expenditures of bulk materials required for the construction of digestion tanks and gasholder are available from Ronchetti (2002). The data is linear adjusted to represent the life time expenditures for a 100'000 PCE plant. The operation of the vessels is assumed to be the same as the total plant (30 years). For stationary machines we assume a life time of 10 years.

In Tab. 12.18 the life cycle data of the infrastructure expenditures for facilities required for the anaerobic treatment of the sewage sludge are summarised.

Tab. 12.18 Unit process raw data of raw sludge fermentation facilities on waste water treatments plants

	Name	Location	InfrastructureProcess	Unit	anaerobic digestion plant, sewage sludge	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	anaerobic digestion plant, sewage sludge	CH	1	unit	1.00E+0			
technosphere	concrete, normal, at plant	CH	0	m3	8.12E+2	1	5.00	literature studies, uncertainties due to variation in plant size
	reinforcing steel, at plant	RER	0	kg	4.87E+4	1	5.00	literature studies, uncertainties due to variation in plant size
	chromium steel 18/8, at plant	RER	0	kg	3.95E+3	1	5.00	literature studies, uncertainties due to variation in plant size
	cast iron, at plant	RER	0	kg	1.01E+3	1	5.00	literature studies, uncertainties due to variation in plant size
transport	transport, lorry 28t	CH	0	tkm	3.84E+4	1	2.09	(4,5,na,na,na,na); standard distances for used materials
	transport, freight, rail	CH	0	tkm	2.78E+4	1	2.09	(4,5,na,na,na,na); standard distances for used materials
disposal	disposal, building, reinforced concrete, to final disposal	CH	0	kg	1.79E+6	1	5.00	literature studies, uncertainties due to variation in plant size
resource, land	Occupation, industrial area, built up	-	-	m2a	3.42E+4	1	1.58	(2,4,2,1,1,5); literature studies, uncertainties due to variation in plant size
	Occupation, construction site	-	-	m2a	3.42E+3	1	1.58	(2,4,2,1,1,5); literature studies, uncertainties due to variation in plant size
	Transformation, from pasture and meadow	-	-	m2	1.14E+3	1	2.07	(2,4,2,1,1,5); literature studies, uncertainties due to variation in plant size
	Transformation, to industrial area, built up	-	-	m2	1.14E+3	1	2.07	(2,4,2,1,1,5); literature studies, uncertainties due to variation in size

12.6.3 Life Cycle Inventories for Raw Sludge Fermentation

Technical characteristics

Sewage gas is produced in digestion tanks and is temporarily stored in gasholders (pressure about 20 mbar). The fermentation process requires electricity for sludge mixing and heat for maintaining a uniform temperature in order to optimise bacterial activity. For sludge digestion usually a temperature between 30 and 40 °C is chosen; i.e. mesophile fermentation (Vogt et al. 2002). In line with Ronchetti (2002) we assume a degradation rate of 45% of organic dry matter and a total share of dry matter in the raw sludge of 4-6%. The products of the fermentation process are sewage gas (also referred to as biogas from sewage sludge digestion) and sewage sludge. For the use of the gas as a fuel for co-generation no further treatment is required.

Raw material input and carbon balance

The input to the digestion process is raw sludge; i.e. a waste product of the successive water treatment. As stated above, expenditures for this process are not included in this study; i.e. all environmental burdens are allocated to the water treatment and not accounted for in the production of sewage gas. The same applies for the further use of digested sewage sludge or an alternative treatment, which are 100% allocated to the wastewater treatment service of the plant, which is not addressed in this project.

As far as the carbon intake in the digestion process is considered; the employed figures are based on our own calculations and derived from the assumed biogas composition and emissions of carbon.

Energy consumption

Energy Consumption figures employed in this research are obtained from Ronchetti (2002), who reported a heat consumption of 10200 kWh/1000 PCE and an electricity consumption of 2300kWh/1000 PCE. Similar as for biowaste digestion, various concepts of energy supply for the digestion of sewage sludge are possible. In principle, if biogas is used as a fuel for co-generation, the heat expenditures can usually covered completely, and electricity demand can be covered partly by the produced heat and electricity from on-site co-generation (Ronchetti et al. 2002). However, this would result in a lower process efficiency of the digestion process; i.e. ideally an adjustment with respect to the final yield of biogas is performed. On the other hand, if biogas is assumed to be used as a feedstock for transportation fuels, the process most likely would be optimised in a way that a maximum yield of biogas is achieved. The reason for this is that a higher biogas throughput in the biogas upgrading plant significantly reduces the cost for the biogas upgrading[24]. In case that all biogas is fed in the upgrading plant, the required heat and electricity is obtained from conventional energy carriers.

The dataset as presented in this study is based on the assumption that biogas is upgraded and used as a fuel. For electricity the current Swiss supply mix is employed. For heat supply various options are possible. In this study we assume that the heat demand is covered by natural gas combustion. Alternatively also wood chips may be used.

Emissions to air

In the below table sources and corresponding quantities of carbon dioxide emissions are summarised. As demonstrated we assume that methane emissions exclusively occur due to leakage of pipes. The underlying values are based on a straightforward calculation and not on measurements.

Tab. 12.19 Carbon dioxide and methane emissions from sewage sludge fermentation

	Unit	Value
Sewage gas production	Nm^3/1000 PCE	9125
Density	kg/Nm^3	1.15
Carbon dioxide content in sewage gas	Nm^3/1000 PCE	3066.00
Methane content in sewage gas	Nm^3/1000 PCE	5748.75
Nitrogen content in sewage gas	Nm^3/1000 PCE	310.25
sewage gas production	kg/ 1000 PCE	10515.31305
Carbon dioxide content in sewage gas	kg/1000 PCE	6054
Methane content in sewage gas	kg/1000 PCE	4095
Nitrogen content in sewage gas	kg/1000 PCE	366
Carbon dioxide emissions excess-gas burning (CH_4 --> CO_2) (5%)	kg/1000 PCE	563
Carbon dioxide emissions excess-gas burning direct from CO2-content in gas (5%)	kg/1000 PCE	303
Methane emissions excess-gas burning (0%)	kg/1000 PCE	0
Carbon dioxide emissions leakage (0.75%)	kg/1000 PCE	45
Methane emissions leakage (0.75%)	kg/1000 PCE	31
Total Carbon Dioxide Emissions	kg/1000 PCE	**911**
Total Methane Emissions	kg/1000 PCE	**31**
Total Carbon Dioxide Emissions	kg/Nm^3	0.100
Total Methane Emissions	kg/Nm^3	0.003

Life cycle inventory input data

In Tab. 12.20 the input data of the biogas upgrading process is presented.

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[24] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

Tab. 12.20 Unit process raw data of anaerobic digestion of raw sludge at a WWTP

	Name	Location	InfrastructureProcess	Unit	biogas, from sewage sludge, at storage	UncertaintyType	StandardDeviation95%	GeneralComment	biogenic carbon content	biogenic carbon balance
	Location				CH					
	InfrastructureProcess				0					
	Unit				Nm3				%	
product	biogas, from sewage sludge, at storage	CH	0	Nm3	1.00000E+00					
	Carbon dioxide, in air	-	-	kg	2.00678E+00	1	1.09	(2,1,1,3,1,3); own calculations	27.3%	0.547
technosphere	heat, natural gas, at boiler condensing modulating >100kW	RER	0	MJ	4.02411E+00	1	1.26	(3,4,2,1,1,5); literature studies and own calculations		
	electricity, low voltage, at grid	CH	0	kWh	2.52055E-01	1	1.26	(3,4,2,1,1,5); literature studies and own calculations		
	transport, lorry 28t	CH	0	tkm	1.42466E-05	1	2.09	(4,5,na,na,na,na); own calculations based on standard transport distances		
	transport, freight, rail	CH	0	tkm	1.70959E-04	1	2.09	(4,5,na,na,na,na); own calculations based on standard transport distances		-
	lubricating oil, at plant	RER	0	kg	2.84932E-04	1	1.26	(3,4,2,1,1,5); literature studies and own calculations		-
	anaerobic digestion plant, sewage sludge	CH	1	unit	3.65297E-08	1	3.07	(3,4,2,1,1,5); literature studies and own calculations		-
emissions to air	Carbon dioxide, biogenic	-	-	kg	9.98540E-02	1	1.07	(1,1,1,3,1,3); literature studies and own calculations	27.3%	0.027
	Methane, biogenic	-	-	kg	3.36575E-03	1	1.51	(2,1,1,3,1,3); literature studies and own calculations	75.0%	2.52E-3
	Heat, waste	-	-	MJ	9.07397E-01	1	1.09	(2,1,1,3,1,3); own calculations		
carbon balance	Carbon input			kg						0.547
	Carbon output (emissions to air)			kg						0.030
	Carbon output (biogas)			kg						0.517
	sum output			kg						0.547

Data quality considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

12.7 Agricultural Fermentation of Manure

12.7.1 System Characteristics

In Fig. 12.2 a schematic process flow sheet for the life cycle of biogas generation from liquid manure and its usage is presented.

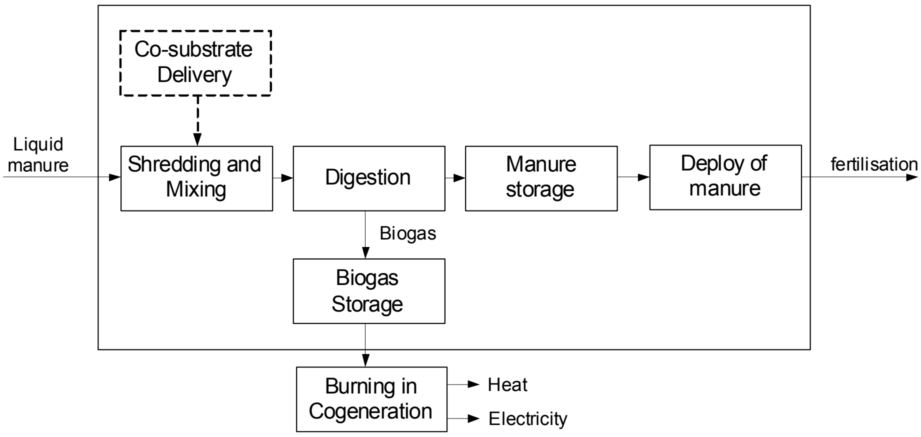

Fig. 12.2 Schematic process flow sheet for the life cycle of biogas generation from liquid manure

Within the system boundaries are the pre-treatment of the substrate in the pit, the digestion process as well as emissions from manure storage and usage as fertiliser that occur in addition to those emissions that would occur from non-digested manure. Since the manure has to be stored in any case, infrastructure expenditures for storage facilities (two storage tanks with a capacity of 410 or 450 m^3) are not accounted for.

The CO_2-fixation in the manure is accounted for as consumption of CO_2 as a resource.

As illustrated in Fig. 12.2, environmental exchanges due to the generation of manure are outside the system boundaries of this study. In contrast, for co-fermentation the transport expenditures for the co-product (biowaste) are inside the system boundaries. The usage of the biogas is not included in this data set. In the subsequent chapter "use and upgrading of biogas" the use of biogas in co-generation is modelled. Data of the plant infrastructure is recorded in a separate data set.

12.7.2 Life Cycle Inventories of Agricultural Biogas Plants

In this study two plants have been studied. The smaller plant with a capacity of $300m^3$ is based on data from plants producing biogas in the year 2004. Typical for these plants is that the stock after the fermentation tank is not covered and the methane produced there will escape. In the last years newer plants are equipped with methane recovery and the average plant size has increased to a capacity of $500m^3$. The standard plant in Switzerland in the year 2006 is a plant with methane recovery in the stock. These plants have been evaluated too.

Plant without methane recovery

In this study we employ data of a typical Swiss plant with a concrete fermentation system in the year 2004. The plant is designed for the digestion of manure of 30 livestock units (LU) cows and 200 pigs (app. 30 LU). In addition, such a plant offers the possibility for the treatment of co-substrates.

The pit is 90 m^3 and the fermenter (digestion facility) has a capacity of about 300 m^3. The lifetime of the plant is assumed to be 20 years.

In Tab. 12.21 the life cycle inventory data of the infrastructure expenditures for the facilities for anaerobic treatment of manure are summarised.

Tab. 12.21 Unit process raw data of the anaerobic digestion plant, agricultural bio waste

Explanations	Name	Location	Infrastructure-Process	Unit	anaerobic digestion plant, agriculture	uncertaintyType	StandardDeviation95%	GeneralComment
	Location InfrastructureProcess Unit				CH 1 unit			
Technosphere	concrete, normal, at plant	CH	0	m3	7.85E+1	1	1.26	(3,4,2,1,1,5); literature studies
	reinforcing steel, at plant	RER	0	kg	6.48E+3	1	1.26	(3,4,2,1,1,5); literature studies
	chromium steel 18/8, at plant	RER	0	kg	7.80E+2	1	1.26	(3,4,2,1,1,5); literature studies
	polystyrene, high impact, HIPS, at plant	RER	0	kg	3.42E+2	1	1.26	(3,4,2,1,1,5); literature studies
	polyvinylchloride, at regional storage	RER	0	kg	4.95E+1	1	1.26	(3,4,2,1,1,5); literature studies
	polyethylene, HDPE, granulate, at plant	RER	0	kg	2.55E+1	1	1.26	(3,4,2,1,1,5); literature studies
	synthetic rubber, at plant	RER	0	kg	1.80E+2	1	1.26	(3,4,2,1,1,5); literature studies
	glued laminated timber, outdoor use, at plant	RER	0	m3	5.54E+0	1	1.26	(3,4,2,1,1,5); literature studies
	copper, at regional storage	RER	0	kg	7.50E+1	1	1.26	(3,4,2,1,1,5); literature studies
	transport, lorry 20-28t, fleet average	CH	0	tkm	6.73E+3	1	2.10	(4,5,na,na,na,na); standard distances for used materials
	transport, freight, rail	CH	0	tkm	2.23E+4	1	2.10	(4,5,na,na,na,na); standard distances for used materials
	disposal, building, reinforced concrete, to final disposal	CH	0	kg	1.79E+5	1	1.26	(3,4,2,1,1,5); literature studies
	disposal, polystyrene, 0.2% water, to municipal incineration	CH	0	kg	3.42E+2	1	1.26	(3,4,2,1,1,5); literature studies
	disposal, polyvinylchloride, 0.2% water, to municipal incineration	CH	0	kg	4.95E+1	1	1.26	(3,4,2,1,1,5); literature studies
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	2.55E+1	1	1.26	(3,4,2,1,1,5); literature studies
	disposal, rubber, unspecified, 0% water, to municipal incineration	CH	0	kg	1.80E+2	1	1.26	(3,4,2,1,1,5); literature studies
	disposal, wood untreated, 20% water, to municipal incineration	CH	0	kg	2.74E+3	1	1.26	(3,4,2,1,1,5); literature studies
resource, land	Occupation, industrial area, built up			m2a	2.22E+3	1	1.58	(2,4,2,1,1,5); literature studies
	Transformation, from heterogeneous, agricultural			m2	1.11E+2	1	2.07	(2,4,2,1,1,5); literature studies
	Transformation, to industrial area, built up			m2	1.11E+2	1	2.07	(2,4,2,1,1,5); literature studies
Outputs	anaerobic digestion plant, agriculture	CH	1	unit	1.00E+0			

Plant with methane recovery

The average Swiss plant in the year 2006 was determined by evaluating 20 plants producing about 50% of the electricity from agricultural biogas plants. A typical Swiss plant has a concrete fermentation system and offers the possibility to treat co-substrates. The pit is 90 m^3 and the fermenter (digestion facility) has a capacity of about 500 m^3. The lifetime of the plant is assumed to be 20 years. A schematic plant design is given in Fig. 12.3.

In table Tab. 12.22 the life cycle inventory data of the infrastructure expenditures for the facilities for anaerobic treatment of manure and co substrate are summarised. Compared to the data given for the plants without covering the following differences occur:

- Because of the larger volume of 500m^3 instead of 300m^3 the major material used, like concrete or reinforcing steel, are use in larger quantities.
- Because of the coverage an amount of 1'200 kg of rubber is used.

Beside these points there are no significant differences.

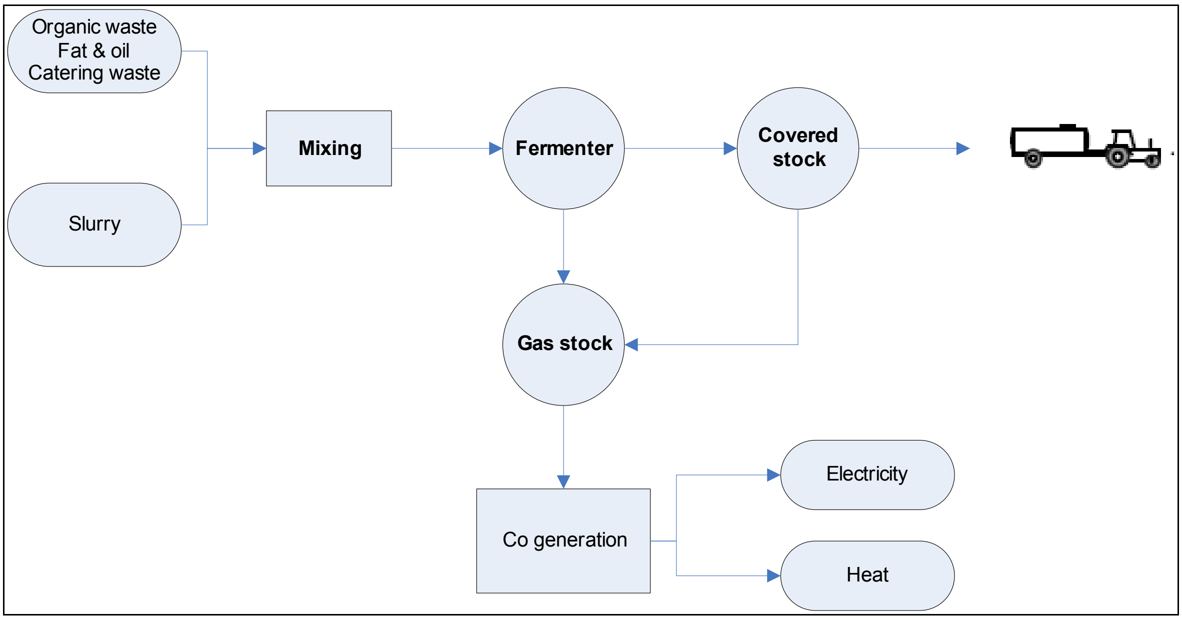

Fig. 12.3 Schematic process flow sheet for co-fermentation in a covered biogas plant

Tab. 12.22 Unit process raw data of the anaerobic, covered digestion plant, agricultural bio waste

	Name	Location	Unit	anaerobic digestion plant covered, agriculture	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location			CH			
	InfrastructureProcess			1			
	Unit			unit			
product	anaerobic digestion plant covered, agriculture	CH	unit	1			
resource, land	Occupation, industrial area, built up	-	m2a	3.60E+3	1	1.51	(2,2,2,1,1,2); Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway. The lifetime is estimated 20 years.
	Transformation, from heterogeneous, agricultural	-	m2	1.80E+2	1	1.51	(2,2,2,1,1,2); Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway. The uncertainty has been estimated.
	Transformation, to industrial area, built up	-	m2	1.80E+2	1	1.51	(2,2,2,1,1,2); Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway. The uncertainty has been estimated.
technosphere	concrete, normal, at plant	CH	m3	1.20E+2	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	reinforcing steel, at plant	RER	kg	1.08E+4	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	steel, converter, chromium steel 18/8, at plant	RER	kg	1.30E+3	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	glued laminated timber, outdoor use, at plant	RER	m3	8.00E+1	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	copper, at regional storage	RER	kg	2.50E+2	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	polystyrene, high impact, HIPS, at plant	RER	kg	5.70E+2	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	polyethylene, HDPE, granulate, at plant	RER	kg	1.70E+2	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	polyvinylidenchloride, granulate, at plant	RER	kg	3.30E+2	1	1.08	(2,2,2,1,1,2); A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	synthetic rubber, at plant	RER	kg	1.20E+3	1	1.08	(2,2,2,1,1,2); Used for coverage. A plant with 500m3 concrete fermenter, average for Swiss agricultural biogas plants in the year 2006 has been used. Only the plants without the stock has been taken into account, Because the stock is needed for the manure anyway.
	transport, lorry 20-28t, fleet average	CH	tkm	7.70E+3	1	2.09	(4,5,na,na,na,na); The transport has been estimated form the amount of material used and average distances
	transport, freight, rail	CH	tkm	1.50E+3	1	2.00	(2,2,na,na,na,na); The transport has been estimated form the amount of material used and average distances
	disposal, building, reinforced concrete, to final disposal	CH	kg	2.99E+5	1	1.08	(2,2,2,1,1,2); Assuming that the concrete will not be reused
	disposal, wood untreated, 20% water, to municipal incineration	CH	kg	6.60E+3	1	1.08	(2,2,2,1,1,2); According to Swiss law organic material has to be burned in incineration plants if no material reuse is possible.
	disposal, polystyrene, 0.2% water, to municipal incineration	CH	kg	5.70E+2	1	1.08	(2,2,2,1,1,2); According to Swiss law organic material has to be burned in incineration plants if no material reuse is possible.
	disposal, polyvinylchloride, 0.2% water, to municipal incineration	CH	kg	3.30E+2	1	1.08	(2,2,2,1,1,2); According to Swiss law organic material has to be burned in incineration plants if no material reuse is possible.
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	kg	1.37E+3	1	1.08	(2,2,2,1,1,2); According to Swiss law organic material has to be burned in incineration plants if no material reuse is possible.

Tab. 12.23 Unit process raw data of the anaerobic, covered digestion plant, agricultural bio waste

ReferenceFunction	401	Name	anaerobic digestion plant covered, agriculture
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	1
ReferenceFunction	403	Unit	unit
DataSetInformation	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	The process includes the production, transport and disposal of the main materials for an agricultural biogas plant.
	404	Amount	1
	490	LocalName	Biogasanlage mit Abdeckung, Landwirtschaft
	491	Synonyms	agricultural co-fermentation plant
	492	GeneralComment	The inventory refers to a typical agricultural biogas plant with a capacity of 500m^3 and a life time of 20 years.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2004
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	This process refers to an agricultural biogas plant with a capacity of about 500m^3. The data were sampled from 20 different plants in Switzerland.
Technology	692	Text	To avoid Methane emissions the new plants in Switzerland are covered.
Representativeness	722	Percent	50
	724	ProductionVolume	70 plants
	725	SamplingProcedure	The data are the average of 20 from 70 plants in Switzerland
	726	Extrapolations	no extrapolation was necessary because the typical plants for the region and time period were evaluated
	727	UncertaintyAdjustments	none
DataGeneratorAndPublic	751	Person	75
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	Biogas
ProofReading	5616	Validator	41
	5615	Details	passed
	5619	OtherDetails	none

12.7.3 Life Cycle Inventories of Manure Fermentation, stock not covered

Technical Characteristics

In the pit manure and co-substrate (as far as co-fermentation is regarded) are mixed and shreddered. Then the prepared mix of manure and co-substrate enters the stoked fermentation facility (35 °C), which is equipped with a mechanical agitator.

The fermentation process requires energy in form of heat to maintain a uniform temperature in order to optimise bacterial activity and electricity for sludge mixing.

In line with (Edelmann 2001) we distinguish between swine and cattle manure. The data presented in this project represents the arithmetical average of swine and cattle manure (mixed manure). In Tab. 12.24 the main characteristics of the input substances and the digestion process are presented. In addition, main characteristic for a co-fermentation (mix co substrate (paunch, oil and vegetable waste) and manure) are summarised.

Tab. 12.24 Characteristics of input substances of the digestion process taken from Edelmann (2001).

	Unit	Cattle manure	Swines manure	Mixed manure	Co-substrat & manure mix
Substance input	t	1.00	1.00	1.00	1
Dry matter	%	9.00	6.00	7.50	12
Organic share in dry matter	%	82.00	78.00	80.00	85
Carbon content of organic matter	%	50.00	50.00	50.00	50
Share of organic substance	kg/tonne	73.80	46.80	60.30	102.00
Total organic decomposition		0.29	0.49	0.39	0.55
Potential Biogas Production	m^3/t Substate	19.93	21.53	20.73	53.08
Total Biogas Production (assumed in this project)	m^3/a	6.24E+04	6.78E+04	6.51E+04	1.04E+05

For a co-fermentation process of manure and co-substrate we assume a daily amount of 2 t/d; i.e. approximately 20% of the manure input.

Raw material input, transport and carbon balance

Manure is a waste product from the animal husbandry and hence all expenditures for the manure production are allocated to the animal husbandry. The same applies for the further use of the digested matter or an alternative treatment, which are 100% allocated to the animal husbandry. As stated above, animal husbandry is outside the system boundaries.

For required transport activities of the co-substrate (7kg/Nm^3), no data was readily available. Thus, assuming that the used co-substrate (paunch, oil and vegetable waste) is obtained from commercial activities rather than from private households, no transport expenditures for bio waste collection from households are required. For transporting the co-substrate from the location of commercial activity to the digestion plant we account for a distance of 17 km (in line with the employed transport distance from collection point to digestion plant as employed in the section bio waste). In contrast to the collection of bio waste – where we distinguished between collected and self-delivered bio waste –, for agricultural fermentation, all transport expenditures are fully allocated to the biogas generation. These results in a slightly higher overall transport demand for manure co-fermentation compared to the bio waste digestion model.

As far as the carbon input in the digestion process is considered; the employed figures are based on our own calculations and derived from the assumed biogas composition and emissions of carbon.

Energy consumption

Energy consumption figures employed in this research are derived from (Edelmann 2001). In Tab. 12.25 energy figures for heat and electricity consumption are summarised. It is assumed that the heat consumption is covered completely by heat delivered from a co-generation unit feed with biogas produced on-site (co-generation unit with ignition gas engine). The electricity demand can only partly be covered with an on-site co-generation unit: 6 MWh and 9 MWh of the total electricity required for manure fermentation and co-fermentation, respectively, are generated by an on-site co-generation unit.

Tab. 12.25 Energy consumption for manure fermentation (figures are obtained via oral communication with Konrad Schleiss (October 2005). Figures for heat consumption differ from (Edelmann 2001).

Energy consumption for digestion		Cattle manure	Swines manure	Mixed manure	Co-Substrat & Mixed Manure
Total Heat Consumption	MJ/a	5.16E+05	5.13E+05	5.14E+05	5.14E+05
Total Electricty Consumption	KWh/a	1.00E+04	1.00E+04	1.00E+04	1.50E+04
Specific Heat Consumption	MJ/m3 biogas	8.27E+00	7.57E+00	7.90E+00	4.96E+00
Specific Electricty Consumption	kWh/m3 biogas	1.60E-01	1.48E-01	1.54E-01	1.45E-01

Emissions to air

As stated above, in this study we only account for those emissions to air, which occur in addition to those emissions that would occur from non-digested manure. In the below table these emissions are summarised. Emissions due to leakages of pipes are not reported in the literature and thus neglected. A comparison between co-fermentation and exclusively manure fermentation reveals higher absolute (yearly) emissions in co-fermentation. However, these higher emissions may be outbalanced as a consequence of the higher gas yield.

Tab. 12.26 Additional airborne emissions that occur from the storage and application of digested manure and which would not occur for non-digested manure (Edelmann 2001).

Emission	Unit	Cattle manure	Swine manure	Mixed manure	Co-substrat & manure mix
Methane	kg/m3*a	4.41	8.15	6.28	9.39
Carbon Dioxide	kg/m3*a	15.79	20.87	18.33	24.9
Ammonia	kg/m3*a	2.12	2.12	2.12	2.26
Methane	kg/a	1323	2445	1884	2817
Carbon Dioxide	kg/a	4737	6261	5499	7470
Ammonia	kg/a	636	636	636	678
Methane	kg/m3 gas	2.12E-02	3.61E-02	2.89E-02	2.72E-02
Carbon Dioxide	kg/m3 gas	7.59E-02	9.24E-02	8.45E-02	7.21E-02
Ammonia	kg/m3 gas	1.02E-02	9.38E-03	9.77E-03	6.54E-03

Allocation

The generation of biogas from liquid manure is exclusively performed to generate biogas (Edelmann 2001). Furthermore, neither an approved quality of the manure used as fertiliser can be quantified nor does space saving in structural works occur as a consequence of the digestion process. Heavy metal emissions due to the application of fertilisers are allocated to the animal husbandry; i.e. they are not considered in this study. In contrast, all emissions directly related to the digestion process are exclusively allocated to the installation and operation of the agricultural biogas generation.

In the case of co-fermentation we merely consider plants which digest less than 3 t bio waste/day. In contrast to bio waste fermentation plants, these plants are not classified as disposal plants in Switzerland. For such plants the use of a co-substrate may be considered as an operating supply item, which aims to increase the yield of the digestion process and guarantee the profitability of the entire process. For the co-fermentation of liquid manure and bio waste no multi-output process is developed, in contrast to the fermentation of bio waste. Thus, additional heavy metal emissions in the application of the manure as a fertiliser are not addressed in this project.

Life cycle inventory input data

In Tab. 12.27 and Tab. 12.28 the input data of the fermentation of manure and co-fermentation of manure and bio waste in an agricultural biogas plant without cover of the stock, respectively, are presented.

Please note that the data for agricultural co-digestion do not include heavy metals coming into the plant with the biowaste. Updated data for new plants can be found in chapter 12.7.4.

Tab. 12.27 Unit process raw data of manure fermentation, not covered

	Name	Location	InfrastructureProcess	Unit	biogas, from agricultural digestion, at storage	UncertaintyType	StandardDeviation95%	GeneralComment	biogenic carbon content	biogenic carbon balance
	Location				CH					
	InfrastructureProcess				0					
	Unit				Nm3				%	
product	biogas, from agricultural digestion, at storage	CH	0	Nm3	1.00000E+00					
technosphere	heat, at cogen with ignition biogas engine, allocation exergy	CH	0	MJ	7.90258E+00	1	1.23	(2,3,2,3,1,5); literature studies		
	electricity, at cogen with ignition biogas engine, allocation exergy	CH	0	kWh	9.21691E-02	1	1.23	(2,3,2,3,1,5); literature studies		
	electricity, low voltage, at grid	CH	0	kWh	6.14461E-02	1	1.23	(2,3,2,3,1,5); literature studies		
	anaerobic digestion plant, agriculture	CH	1	unit	7.68076E-07	1	3.07	(3,3,2,3,1,5); literature studies		
emissions to air	Carbon dioxide, biogenic	-	-	kg	8.44700E-02	1	1.25	(1,3,3,3,1,5); literature studies and own calculations	27.3%	0.023
	Methane, biogenic	-	-	kg	2.89401E-02	1	1.64	(3,3,4,3,1,5); literature studies	75.0%	0.022
	Ammonia	-	-	kg	6.54124E-03	1	1.39	(2,3,4,3,1,5); literature studies	0.0%	-
resource	Carbon dioxide, in air	-	-	kg	2.10943E+00	1	1.32	(2,3,4,3,1,5); own calculations	27.3%	0.575
waste	Heat, waste	-	-	MJ	5.53015E-01	1	1.32	(2,3,4,3,1,5); own calculations	0.0%	-
	Carbon input			kg						0.575
	Carbon output (emissions to air)			kg						0.045
	Carbon output (biogas)			kg						0.531
	sum output			kg						0.575

Tab. 12.28 Unit process raw data of the anaerobic co-fermentation of manure and co-substrate, not covered

	Name	Location	InfrastructureProcess	Unit	biogas, from agricultural co-digestion, at storage	UncertaintyType	StandardDeviation95%	GeneralComment	biogenic carbon content	biogenic carbon balance
	Location				CH					
	InfrastructureProcess				0					
	Unit				Nm3				%	
product	biogas, from agricultural co-digestion, at storage	CH	0	Nm3	1.000E+00					
technosphere	transport, lorry 28t	CH	0	tkm	1.196E-01	1	2.06	(2,3,2,3,1,5); literature studies and own calculations		
	heat, at cogen with ignition biogas engine, allocation exergy	CH	0	MJ	4.957E+00	1	1.23	(2,3,2,3,1,5); literature studies		
	electricity, at cogen with ignition biogas engine, allocation exergy	CH	0	kWh	8.672E-02	1	1.23	(2,3,2,3,1,5); literature studies		
	electricity, low voltage, at grid	CH	0	kWh	5.781E-02	1	1.23	(2,3,2,3,1,5); literature studies		
	anaerobic digestion plant, agriculture	CH	1	unit	4.818E-07	1	3.07	(3,3,2,3,1,5); literature studies		
emissions to air	Carbon dioxide, biogenic	-	-	kg	7.197E-02	1	1.25	(1,3,3,3,1,5); literature studies	27.3%	0.020
	Methane, biogenic	-	-	kg	2.714E-02	1	1.64	(3,3,4,3,1,5); literature studies	75.0%	0.020
	Ammonia	-	-	kg	6.533E-03	1	1.39	(2,3,4,3,1,5); literature studies	0.0%	-
waste	Heat, waste	-	-	MJ	5.203E-01	1	1.32	(2,3,4,3,1,5); own calculations	0.0%	-
resource	Carbon dioxide, in air	-	-	kg	2.092E+00	1	1.32	(2,3,4,3,1,5); own calculations	27.3%	0.571
	Carbon input			kg						0.571
	Carbon output (emissions to air)			kg						0.040
	Carbon output (biogas)			kg						0.531
	sum output			kg						0.571

Data quality considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

12.7.4 Life Cycle Inventories of agricultural co-fermentation

The evaluation of the data set described in 12.7.3 has shown a high relevance of the methane emissions concerning the global warming potential (Zah 2007). The reason for these emissions is the fact, that a certain amount of methane is formed in the stock after the fermentation. If this stock is not covered the methane will escape into the atmosphere. In the data set referring to the year 2004 an emission of 5% methane has been used. In the last two years the new plants have a covered stock to collect methane and reduce the emissions of methane to the air by 80% down to 1% (Edelmann 2001). To take into account the new developments 20 biogas plants have been evaluated for the year 2006, see Tab. 12.29. All these plants are equipped with a co-generation power plant to produce electricity. The evaluated plants are representative for the situation in Switzerland in the year 2006 because they produce about 50% of the electricity from agricultural plants.

Tab. 12.29 Characteristics of the evaluated plants, only the plants with covered stock have been taken into account. Data source: naturemade, VUE Verein für umweltgerechte Elektrizität, Zurich.[25]

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[25] Nadine Guthapfel (Mai 2007)

plant:	type	covered	size	total inputl	Co-Substrate	transport co-substrate	electricity from the grid	electricity used / Nm3 biogas	biogas use for electricity (measured)	power co generation plant	typ of cogen plant	net electricity production	sold heat	slurry spreading
			[m^3]	[t]	[t]	[km]	[MWh]	[kWh]	[Nm^3]	[kW]		[MWh]	[MJ]	
1	concrete	yes	1000	2'625	555	33.9	50	0.161	310'000	140	biogas engin	720	396'000	trail hose
2	concrete	yes	580	2'705	705	0.8	50	0.217	230'000	100	biogas engin	550	399'600	trail hose
3	concrete	yes	475	3'425	1'225	2.9	20	0.074	270'000	100	biogas engin	490	3'600	trail hose
4	concrete	yes	1200	6'800	1'800	9		-	730'000	190	biogas engin	1200	2'491'200	trail hose
6	concrete	yes	280	3'060	1'185	5.9		-	120'000	65	ignition	250	147'600	trail hose
8	concrete	yes	475	2'140	905	7		-	380'000	100	biogas engin	700	540'000	trail hose
10	concrete	yes	700	5'106	3'786	38.6		-	500'000	157	biogas engin	1200	1'512'000	trail hose
11	concrete	yes	600	7'838	418	2.2	50	0.097	515'000	290	biogas engin	1200	360'000	trail hose
12	concrete	yes	500	3'948	1'090	4		-	380'000	100	biogas engin	700	784'800	normal
13	concrete	yes	400	3'399	1'094	4	50	0.152	328'000	100	ignition	619	180'000	trail hose
14	concrete	yes	1000	5'160	1'500	4.6	50	0.179	280'000	100	biogas engin	650	1'008'000	normal
16	concrete	yes	492	3'205	900	9.2	10	0.026	380'000	100	biogas engin	700	216'000	trail hose
18	steel	yes	400	6'088	2'575	25		-	350'000	155	ignition	817.3	1'980'000	trail hose
20	concrete	yes	400	1'682	412	100	25	0.147	170'000	65	ignition	350	396'000	trail hose
Total: covered plants				**57'181**	**18'150**		**305**		**4'943'000**			**10'146**		
median			496	3'412	1'092	6.45	50.0	0.150	339'000	100.0		700.0	397800.0	
average			607	4'084	1'296	17.65	38.1	**0.132**	353'071	125.9		724.7	743914.3	
std dev.			272	1'840	920	26.6	16.9	0.062	154'366	58.9		298.2	748960.6	
5	concrete	no	160	1227	222	0.4			75'000	50	ignition	160	57	trail hose
7	concrete	no	560	3099	770	4.7	50	0.187	268'000	100	ignition	510	100	trail hose
9	concrete	no	492	3925	1229	2.9	60	0.261	230'000	100	biogas engin	600	50	trail hose
15	concrete	no	470	2104	514	1.8			230'000	100	ignition	500	450	trail hose
17	concrete	no	400	1808	608	10.5			130'000	100	ignition	310	77.3	trail hose
19	steel	no	400	2700	1045	5	10	0.046	218'400	80	ignition	520	40	normal
Total: non covered plants				**14'863**	**4'388**		**120**		**1'151'400**			**2'600**		
Total over all plants				**72'044**	**22'538**		**425**		**6'094'400**			**12'746**	**3'667**	
median			483.5	3'152	975	4.85	50.0	0.152	275'000	100		609.5	105	
average			549.2	3'602	1'127	13.62	38.6	0.141	304'720	114.6		637.3	183.4	
std. dev.			253.2	1'770	827	23.0	18.5	0.073	153'172	52.9		294.5	193.8	

These investigations lead to the following findings:

- The average size is 500m^3 in the year 2002 the average fermenter size was 300m^3
- Two third of the plants have a covered stock. The others will realize this in the year 2007.
- The new co generation plants are using biogas engines instead of the ignition engines used in the older plants.
- 90% of the plants have a fermentation tank of concrete and 10% have one made of steel.
- In these 20 plants about 50’000 t of manure and 22’500 t of co-substrate have been processed and produced about 6’000’000 m^3 of biogas.

In the following table the inputs and the produced biogas are given for the year 2006. The data are based on a written communication from naturemade, VUE Verein für umweltgerechte Elektrizität, Zürich.[26]

Tab. 12.30 Input used in the evaluated biogas plants

All plants	t FM	t DM	t OM	* m^3 biogas /t FS	total m^3 biogas
fat & oil	5'258	2'629	2'366	450	2'366'100
cereals	1'588	1'270	1'016	320	508'160
catering waste	6'867	1'373	1'167	136	933'912
Vegetables and organic waste	8'394	1'175	940	67	564'077
Sum co-substrate	**22'107**	**6'448**	**5'490**		**4'372'249**
Liquid manure	49'506			34.8	1'722'151
Total biogas					**6'094'400**

FM: fresh mass, DM: dry matter, OM: organic matter

* source: Baserga Urs 2000. The values given in this publication have been compared with data given for Germany (FNR 2005)

About 70% of the biogas was produced by the co substrate with a share of 30% concerning the fresh mass. The most important contribution is given by the fat, oils and glycerine. Because of the importance of the fat and the other co-substrates and the fact that the distribution of the co-substrates can change in short time according to the market situation we decide to model the situation in the following way, see Fig. 12.3:

A multi output process for bio waste to agricultural co-fermentation, with the following three outputs or services has been created:

- Disposal of bio waste
- Biogas from bio waste
- Application of digested matter

This process includes the catering waste and the vegetable and organic waste. For the calculations the sums respectively the weighted averages have been used. The weighted average for the biogas produced from 1 t of fresh matter is 102 Nm^3.

Another multi output process for fat & oil to agricultural co-fermentation, with the two outputs or services:

- Disposal fat & oil

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[26] Nadine Guthapfel (Mai 2007)

- Biogas from fat & oil

In accordance with the production of XME from waste cooking oil, the oil has been considered to be a waste for disposal without economical value. In contrast to the process producing XME no purification step for the waste oil is needed if it is used in a biogas plant. This process includes the fat & oil and the cereals. For the calculations the sums respectively the averages have been used.

A further process for biogas from slurry (liquid manure) in agricultural co-fermentation with a covered stock has been created.

This process structure gives the possibility to make a model for biogas production in agriculture co-fermentation by changing the inputs. Important is to take into account the fact, that it is not possible to digest fat & oil or catering waste alone. For fat & oil a maximum share of 10% cannot be exceeded, for catering waste the maximum share must be less than around 25%. So the processes for co-fermentation of fat & oil and bio waste can not be used for it's own but only together with the process for slurry.

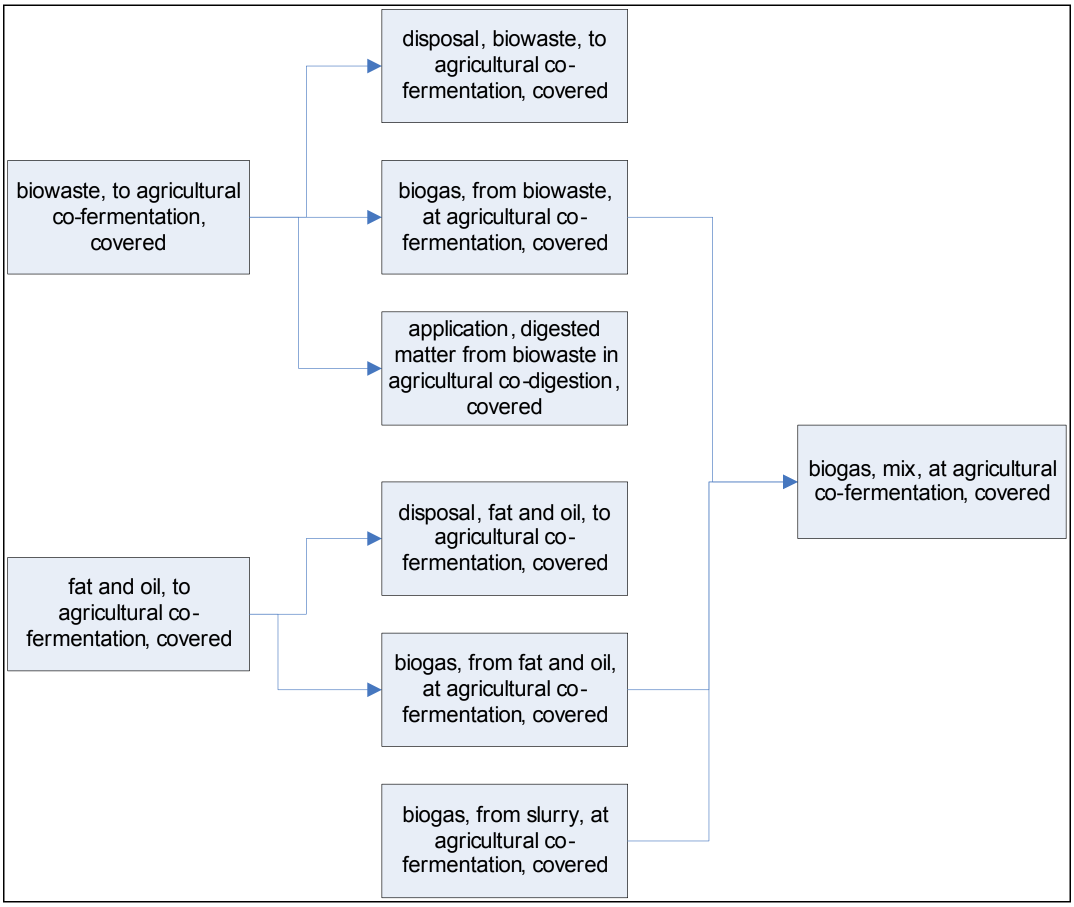

Fig. 12.4 **Processes to model the biogas from agricultural co-fermentation**

Biogas from slurry at agricultural co-fermentation with covered stock

As outlined in chapter 12.7.3 the generation of biogas from liquid manure is exclusively performed to generate biogas (Edelmann 2001). Furthermore, neither an approved quality of the manure used as fertiliser can be quantified nor does space saving in structural works occur as a consequence of the digestion process. Heavy metal emissions due to the application of fertilisers for digested slurry are allocated to the animal husbandry; i.e. they are not considered in this study. For biogas from bio waste all emissions from the spreading of the digested matter have been taken into account, according to the composition of the bio waste, see Tab. 12.2. Because of the fact that fat & oil do not contain heavy metals, according to Betsche (1999) and no nitrogen, no such emissions have been taken into account.

In contrast, all emissions directly related to the digestion process are exclusively allocated to the installation and operation of the agricultural biogas generation.

Methane emission

To evaluate the methane emissions from the covered plants different studies on this topic have been evaluated. The emissions given in the literature differs according to the differences in the processes and the treatments, but all show a high reduction potential for covered stocks compared to uncovered stocks.

Tab. 12.31 Methane emissions from agricultural biogas plants

Reference	share of biogas for uncovered stock	share of biogas for covered stock
Rieger & Weiland in Clemens (2006)	up to 10%	
Neukomm[27]	10 – 12%	
Wartmann, Engeli 2002	0.5 – 1%	
Wulf S. et al. 2006		0%[28]
Berglund Maria, 2006		0.5% - 1%
Scholwin F. 2006		Only qualitative statement: high reduction due to covered stock
Wellinger[29]		1 – 4%
Edelmann et al. 2001		1%
Used values in this studies	**5%**	**1%**

According to the data in the table above the emissions of methane can be reduced by 80% due to the covering of the stock.

The energy used per Nm^3 of biogas of the investigated plants in the year 2006 is in good accordance with the values used for the plants in the year 2004. The median of the electricity used is 0.15 kWh/Nm^3, the average is 0.132 kWh/Nm^3 so a value of 0.14 kWh/Nm^3 has been used.

Ammonia and dinitrogen monoxide emissions

In the literature no quantitative new data has been found. So the same emission values as for the non covered fermentation plant have been used, see chapter 12.7.3, because the coverage of the stock has no effect on the ammonia or dinitrogen monoxide emissions. The inventory is given in Tab. 12.32.

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[27] Herr Neukomm, Thayngen, personal communication (Mai 2007)

[28] Not representative for Swiss plants, because in this study a zero emission from the stock has been assumed.

[29] Wellinger Arthur, personal written communication, (November 2006), Novoenergie, Aadorf

Tab. 12.32 Unit process raw data of the anaerobic co-fermentation of liquid manure with a covered stock to avoid methane emissions

	3702	3703	3706	3707	3708	3709	3792		
	Name	Location	Unit	biogas, from slurry, at agricultural co-fermentation, covered	UncertaintyType	Standard Deviation 95%	GeneralComment	Biogenic carbon content	biogenic carbon balance
	Location			CH					
	InfrastructureProcess			0					
	Unit			Nm3					
product	biogas, from slurry, at agricultural co-fermentation, covered	CH	Nm3	1				53.06%	0.5306
technosphere	anaerobic digestion plant covered, agriculture	CH	unit	1.64E-7	1	1.09	(2,3,1,1,1,2); plant producing 300'000m3 biogas, lifetime 20 years		
	electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	CH	kWh	5.25E-2	1	1.10	(2,3,2,1,1,2); avarage electricity used from internal cogeneration. Evaluation of 20 plants producing about 50% of the electricity from agricultural biogas plants in Switzerland.		
	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	CH	kWh	1.75E-2	1	1.10	(2,3,2,1,1,2); avarage electricity used from internal cogeneration. Evaluation of 20 plants producing about 50% of the electricity from agricultural biogas plants in Switzerland.		
	heat, at cogen with biogas engine, agricultural covered, allocation exergy	CH	MJ	5.93E+0	1	1.10	(2,3,2,1,1,2); avarage heat used from internal cogeneration. Evaluation of 20 plants producing about 50% of the electricity from agricultural biogas plants in Switzerland.		
	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	CH	MJ	1.98E+0	1	1.10	(2,3,2,1,1,2); avarage heat used from internal cogeneration. Evaluation of 20 plants producing about 50% of the electricity from agricultural biogas plants in Switzerland.		
	electricity, low voltage, at grid	CH	kWh	6.97E-2	1	1.10	(2,3,2,1,1,2); avarage electricity used from the grid. Evaluation of 20 plants producing about 50% of the electricity from agricultural biogas plants in Switzerland.		
emission air, low population density	Carbon dioxide, biogenic	-	kg	6.29E-3	1	1.10	(2,3,2,1,1,2); The stock is covered to avoid methane emissions. So the emission is about 1%. In consequence also the CO2 emissions are reduced.	27.27%	0.0017
	Ammonia	-	kg	6.54E-3	1	1.30	(4,3,2,1,1,2); Difference of ammonia emissions compared to the un-fermented manure.		
	Dinitrogen monoxide	-	kg	2.04E-3	1	1.57	(4,3,2,1,1,2); Calculated from the ammonia emissions		
	Methane, biogenic	-	kg	4.79E-3	1	1.57	(4,3,2,1,1,2); The stock is covered to avoid methane emissions. So the emission is about 1%.	75%	0.0036
	Heat, waste	-	MJ	5.03E-1	1	1.22	(4,3,2,1,1,2); own calculation from electricity use		
resource, in air	Carbon dioxide, in air	-	kg	1.96E+0	1	1.10	(2,3,2,1,1,2); The carbon dioxide fixation in the biowaste is accounted for as CO2 as ressource. The actual value is based on the biowaste composition.	27.27%	0.5359
Carbon balance	Carbon input								**0.5359**
	Carbon output (emissions to air								0.0053
	Carbon output (in biogas)								0.5306
	Total output								**0.5359**

Tab. 12.33 Meta information of the anaerobic co-fermentation of liquid manure with a covered stock to avoid methane emissions

ReferenceFunction	401	Name	biogas, from slurry, at agricultural co-fermentation, covered
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	The process invludes the energy use and the infrastructure used to produce 1 Nm3 of biogas from manure in a plant with a covered stock to recover the methan emissions
	404	Amount	1
	490	LocalName	Biogas, aus Gülle, ab landwirtschaftliche Kovergärung, mit Abdeckung
	491	Synonyms	
	492	GeneralComment	The invetory refers to a typical agricultaral biogas plant in the year 2006 with a capacity of 500m^3 and a life time of 20 years.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	This process refers to an agricultural biogas plant with a capoacity of about 500m^3. The data were sampled from 20 differnet plants in Switzerland.
Technology	692	Text	To avoid Methan emissions the new plants in Switzerland are covered, to reduce NH3 emissions the digested matter will be spread with a trail hose.
Representativene	722	Percent	
	724	ProductionVolume	12 mio. m3 Biogas
	725	SamplingProcedure	The data are the average of 20 plants in Switzerland to produce electricity according the criteria of "naturemade"
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	75
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Biogas from co-substrate at agricultural co-fermentation with covered stock

As shown in Fig. 12.4 different co-substrate are added to the manure to increase the biogas production. For this process it was assumed that the energy needs per Nm^3 of biogas will not have significant change dependent on the composition of the co-substrate. This assumption is based on the comparison between the electricity consumption of manure fermentation and manure co-fermentation showing a difference in the electricity consumption of less than 10%. It is why the same average electricity need was used for all co-substrate. But an important question concerns the allocation of the emissions and the needed resources.

Allocation

The principle question with respect to allocation of emissions in the biogas generation process is, whether the biogas generation is considered as a waste treatment process or as a "production" process. Currently, separate treatment of biogas is motivated by cost reduction and waste management policies. Furthermore, as stated above, the digestion process yields two additional products: press water and digested matter, which are used as a fertiliser in agriculture.

In this study, we assume that bio waste treatment fulfils three functions:

- Disposal of bio waste,
- production of biogas,
- production and use of press water and digested matter as fertiliser in agriculture

Consequently, the generation of biogas from bio waste and from fat & oil is modelled in a multi-output process. The allocation is based on economic figures. In the last years the price paid for the disposal of bio waste in agriculture co-fermentation has decreased because of competition. Today an agricultural co-fermentation plant gets about 40 CHF / t of bio waste or fat & oil. For glycerine there is a change in the market. In the year 2006 and the previous years glycerine has to be considered as waste because the owner of glycerine has to pay for disposal. Since the year 2007 sometimes glycerine can be sold earning up to 40 CHF / t. So for future analysis this has to be taken into account.

There is a wide range given for the revenue of biogas. The German "Fachverband Bioenergie" suggested a compensation of 5-10 cents/kWh for the feeding of biogas in the gas or electricity network (IWR 2001). Mr. Zeifang from KOMPOGAS reported a quantity of 0.04 CHF/kWh[30]. The biogas plants we looked at in this project are producing electricity according to the naturemade standard. They get about 0.22 – 0.25 CHF / kWh electricity. So there is a wide range of revenues reported. We used a value of 0.23 CHF / kWh electricity. This choice is based on the fact, that today normally the agricultural biogas plants produce electricity and this value is in between the other two values. Press water and digested matter are usually given to the farmers free of charge. Consequently, for the production of press water and digested matter no environmental burdens are accounted for. On the other hand, emissions that occur during the application and use of fertilisers in agriculture are merely allocated between the application of press water and digested matter as a fertiliser and the disposal of bio waste. In this study, we pursued a practical approach and allocated 50% of the environmental exchanges occurring in the use of the press water and digested matter to the production of fertiliser and 50% to the disposal service of bio waste.

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[30] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

Tab. 12.34 Allocation factors according to the economic revenues

		Revenue CHF / t		
			Biogas	
	m^3 Biogas /t FM	electricity	low price	high price
fat & oil	450	216	130	325
cereals	320	154	92	231
catering waste	136	65	39	98
bio waste	67	32	19	49

Allocations	CHF		%	
	disposal	biogas	disposal	biogas
fat & oil, cereals	40	185	18%	82%
catering & bio waste	40	33	55%	45%

For bio waste the mean value between catering waste and bio waste has been chosen. This leads to an allocation factor of 55% for disposal and 45% for biogas. Compared to the allocation factors for bio waste in an anaerobic digestion plant, see chapter 12.5.3 the allocation factor for biogas is 2.5 times higher in the agricultural plant. The reasons for this higher allocation of the environmental impacts to the biogas are:

- With the production of electricity certified naturemade star better revenue can be achieved with the biogas
- The price for the disposal service is lower for the materials disposed in agricultural plants. This is an effect of the competition in this market. According to the experience of K. Schleiss in the last years the prices have fallen. For waste with a high energetic value like glycerine the owner of the plant has since 2007 sometimes to pay for this waste fraction.

This results shows that the results are sensitive to the prices and the resulting allocations. To analyse specific systems it can be necessary to take into account the given situation and adopt the process and the allocation.

Tab. 12.35 Unit process raw data of fat & oil in agricultural co-fermentation, covered

	401	InputGroup	OutputGroup	Name	Location	Infrastructure Process	Unit	fat and oil, to agricultural co-fermentation, covered	UncertaintyType	StandardDeviation95%	GeneralComment	disposal, fat and oil, to agricultural co-fermentation, covered	biogas, from fat and oil, at agricultural co-fermentation, covered	Biogenic carbon content	biogenic carbon balance
	662			Location				CH				CH	CH		
	493			InfrastructureProcess				0				0	0		
	403			Unit				kg				kg	Nm3		
allocated		-	2	disposal, fat and oil, to agricultural co-fermentation, covered	CH	0	kg	1.00E+0				100	0	24%	-0.239
products		-	2	biogas, from fat and oil, at agricultural co-fermentation, covered	CH	0	Nm3	4.46E-1				0	100	53.06%	0.236
technosphere		5	-	anaerobic digestion plant covered, agriculture	CH	1	unit	6.31E-8	1	1.22	(2,3,1,3,1,5); plant producing 300'000m3 biogas, lifetime 20 years	-	100.0		
		5	-	electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	CH	0	kWh	2.02E-2	1	1.09	(2,3,1,3,1,2); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants produce their own electricity	18.0	82.0		
		5	-	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	CH	0	kWh	6.61E-3	1	1.09	(2,3,1,3,1,2); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants produce their own electricity	18.0	82.0		
		5	-	heat, at cogen with biogas engine, agricultural covered, allocation exergy	CH	0	MJ	2.28E+0	1	1.09	(2,3,1,3,1,2); The needed heat is produced by the cogeneration	18.0	82.0		
		5	-	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	CH	0	MJ	7.62E-1	1	1.09	(2,3,1,3,1,2); The needed heat is produced by the cogeneration	18.0	82.0		
		5	-	transport, lorry 20-28t, fleet average	CH	0	tkm	1.93E-2	1	2.01	(2,3,1,3,1,2); The transport for the co-substrate of 20 plants producing about 50% of the agricultural biogas have been evaluated.	18.0	82.0		
		5	-	electricity, low voltage, at grid	CH	0	kWh	2.68E-2	1	1.09	(2,3,1,3,1,2); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants uses electricity from the grid	18.0	82.0		
emission air, low population density		-	4	Carbon dioxide, biogenic	-	-	kg	8.78E-1	1	1.09	(2,3,1,3,1,2); The stock is covered to avoid methane emissions. So the emission is about 1%.	99.6	0.4	27.27%	0.24
		-	4	Methane, biogenic	-	-	kg	2.13E-3	1	1.62	(4,3,2,3,1,5); The stock is covered to avoid methane emissions. So the emission is about 1%.	18.0	82.0	75%	0.0016
		-	4	Heat, waste	-	-	MJ	1.93E-1	1	1.23	(2,3,2,3,1,5); Own calculation from electricity input	18.0	82.0		
resource, in air		4	-	Carbon dioxide, in air	-	-	kg	8.75E-1	1	1.23	(2,3,2,3,1,5); The carbon dioxide fixation in the bio waste is accounted for as CO2 as resource. The actual value is based on the bio waste composition.	-	100.0	27.27%	0.2388
Carbon balance				$C_{in,pre-product}$									0.239		**0.2388**
				$C_{out, emissions}$								0.00029	0.001		**0.0024**
				$C_{out, process-output}$								-0.23876	0.236		0.2364
				$C_{out, emissions, CO2}$ (calculated)								0.23847	0.001	-	**0.2395**
				Input - Output								-	-	-	-

Tab. 12.36 Unit process raw data of fat & oil in agricultural co-fermentation, covered, meta information

ReferenceFunction	401		fat and oil, to agricultural co-fermentation, covered
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	kg
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	
	404	Amount	1
	490	LocalName	Fett und Öl, in landwirtschaftliche Kovergärung, mit Abdeckung
	491	Synonyms	
	492	GeneralComment	This process cannot be used for its own. It can only be used as a auxilliary process for the process "biogas, mix, at agricultural co-fermentation, covered" to give to the user the possiblity to calculate biogas production with differnt inputs. The multioutput-process "fat and oil to agricultural co-fermentation, covered" delivers the co-products "disposal, fat and oil, to agricultural co-fermentation, covered" and "biogas, from fat and oil, at agricultural co-fermentation, covered". The allocation is based on economic criteria.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2006-01-01
	602	EndDate	2006-12-31
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	Avarage swiss technology
Technology	692	Text	Fermenter with methane recovery
Representativene	722	Percent	60
	724	ProductionVolume	
	725	SamplingProcedure	
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	82
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	Chapter 1.7.4
ProofReading	5616	Validator	41
	5615	Details	automatic validation in Excel
	5619	OtherDetails	none

Tab. 12.37 Unit process raw data of bio waste in agricultural co-fermentation, covered

	Name	Location	InfrastructureProcess	Unit	biowaste, to agricultural co-fermentation, covered	UncertaintyType	StandardDeviation95 %	GeneralComment	disposal, biowaste, to agricultural co-fermentation, covered	biogas, from biowaste, at agricultural co-fermentation, covered	application, digested matter from biowaste in agricultural co-digestion, covered	Biogenic carbon content	biogenic carbon balance
	Location				CH				CH	CH	CH		
	InfrastructureProcess				0				0	0	0		
	Unit				kg				kg	Nm3	kg		
allocated	disposal, biowaste, to agricultural co-fermentation, covered	CH	0	kg	1.00E+0				100	0	0	-16.2%	-0.16200
products	biogas, from biowaste, at agricultural co-fermentation, covered	CH	0	Nm3	1.01E-1				0	100	-	53.1%	0.05383
products	application, digested matter from biowaste in agricultural co-digestion, covered	CH	0	kg	7.12E-1				0	-	100	10.2%	0.07262
technosphere	anaerobic digestion plant covered, agriculture	CH	1	unit	1.67E-8	1	1.23	(2,3,2,3,1,5); plant producing 300'000m3 biogas, lifetime 20 years	-	100.0	-		
	electricity, at cogen with biogas engine, agricultural covered, alloc. exergy	CH	0	kWh	5.36E-3	1	1.23	(2,3,2,3,1,5); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants produce their own electricity	55.0	45.0	-		
	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	CH	0	kWh	1.75E-3	1	1.23	(2,3,2,3,1,5); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants produce their own electricity	55.0	45.0	-		
	heat, at cogen with biogas engine, agricultural covered, allocation exergy	CH	0	MJ	6.05E-1	1	1.23	(2,3,2,3,1,5); Needed heat is produced by the cogeneration	55.0	45.0	-		
	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	CH	0	MJ	2.02E-1	1	1.25	(2,3,3,3,1,5); Needed heat is produced by the cogeneration	55.0	45.0	-		
	transport, lorry 20-28t, fleet average	CH	0	tkm	5.10E-3	1	2.01	(2,3,1,2,1,3); The transport for the co-substrate of 20 plants producing about 50% of the agricultural biogas have been evaluated.	55.0	45.0	-		
	electricity, low voltage, at grid	CH	0	kWh	7.11E-3	1	1.25	(2,3,3,3,1,5); Evaluation of 20 plants producing about 50% of the agricultural biogas. Half of the plants uses electricity from the grid	55.0	45.0	-		
emission air, low population density	Carbon dioxide, biogenic	-	-	kg	7.23E-1	1	1.25	(2,3,3,3,1,5); The stock is covered to avoid methane emissions. So the emission is about 1%.	82.1	17.8	0.1	27.27%	0.1972
	Ammonia	-	-	kg	6.67E-4	1	1.33	(2,3,3,3,1,5); Difference of ammonia emissions compared to the un-fermented manure.	47.3	38.6	14.2		
	Dinitrogen monoxide	-	-	kg	2.09E-4	1	1.58	(2,3,3,3,1,5); Proportional to the ammonia emission	47.3	38.6	14.2		
	Methane, biogenic	-	-	kg	4.88E-4	1	1.58	(2,3,3,3,1,5); The stock is covered to avoid methane emissions. So the emission is about 1%.	55.0	45.0	-	75%	0.00037
	Heat, waste	-	-	MJ	5.12E-2	1	1.25	(2,3,3,3,1,5); own calculations from electricity used	55.0	45.0	-		
	Hydrogen sulfide	-	-	kg	2.45E-4	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	55.0	45.0	-		
emission soil, agricultural	Phosphorus	-	-	kg	1.13E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Boron	-	-	kg	1.02E-5	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Chloride	-	-	kg	4.00E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Bromine	-	-	kg	6.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Fluoride	-	-	kg	2.00E-4	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Arsenic	-	-	kg	2.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Cadmium	-	-	kg	1.38E-7	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Cobalt	-	-	kg	5.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Chromium	-	-	kg	8.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Copper	-	-	kg	1.80E-5	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Iodide	-	-	kg	5.50E-8	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Mercury	-	-	kg	7.00E-8	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Manganese	-	-	kg	4.30E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Molybdenum	-	-	kg	4.00E-7	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Nickel	-	-	kg	5.42E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Nitrogen	-	-	kg	3.68E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Lead	-	-	kg	1.86E-5	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Selenium	-	-	kg	5.00E-7	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Sulfur	-	-	kg	1.50E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Tin	-	-	kg	8.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Vanadium	-	-	kg	3.00E-6	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Zinc	-	-	kg	5.82E-5	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Silicon	-	-	kg	4.00E-2	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Iron	-	-	kg	6.00E-4	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Calcium	-	-	kg	2.18E-2	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Aluminum	-	-	kg	1.00E-2	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Potassium	-	-	kg	3.50E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Magnesium	-	-	kg	2.82E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
	Sodium	-	-	kg	1.50E-3	1	1.60	(3,3,3,3,1,5); Literature studies done for the process bio waste to anaerobic digestion	50.0	-	50.0		
resource, in air	Carbon dioxide, in air	-	-	kg	5.94E-1	1	1.27	(3,3,3,3,1,5); The carbon dioxide fixation in the bio waste is accounted for as CO2 as resource. The actual value is based on the bio waste composition.	-	55.0	45.0		
Carbon balance	$C_{in,pre-product}$								-	0.0891	0.0729		**0.1620**
	$C_{out, emissions}$								0.0002	0.00016	-		0.0004
	$C_{out, process-output}$								-0.162	0.05383	0.0726		-0.0355
	$C_{out, emissions, CO2}$ (calculated)								0.162	0.0351	0.0003		**0.1972**
	Input - Output								-	-	-		-

Tab. 12.38 Unit process raw data of bio waste in agricultural co-fermentation, covered, meta information

ReferenceFunction	401		biowaste, to agricultural co-fermentation, covered
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	kg
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	This process contains the infrastructure, the energy used and the emissions of the fermetation process.
	404	Amount	1
	490	LocalName	Bioabfall, in landwirtschaftliche Kovergärung, mit Abdeckung
	491	Synonyms	
	492	GeneralComment	This process can only be used together with the process "biogas, mix, at agricultural co-fermentation, covered" because biowaste is not treated in agricultural biogas plants alone but only together with liquid manure. This process has been genereated to give the possibility to model co-fermentation with different inputs. The multioutput-process "biowaste, to agriculture co-fermentation, covered" delivers the co-products "biogas", "application of digestet matter" and the service "disposal of bio waste". The functional unit refers to 1 kg fresh matter of vegetable and organic waste and catering waste. The allocation is based on economic criteria.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	This dataset is valid for agricultural plants in Switzerland in the year 2006
Technology	692	Text	To reduce methan emission the stock container is covered, to reduce NH3 emissions the digested matter will be spread with a trail hose.
Representativene	722	Percent	50
	724	ProductionVolume	12 mio. m3 Biogas
	725	SamplingProcedure	field data, The data are the average of 20 plants in Switzerland to produce electricity according the criteria of "naturemade".
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	75
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Biogas from co-substrate at agricultural co-fermentation with covered stock

To calculate the biogas mix for the year 2006 for the plant with a covered stock have been evaluated according to the used manure and waste. The shares of the different fraction are given in the Tab. 12.39. The data are based on a written communication from Naturemade, VUE Verein für umweltgerechte Elektrizität, Zürich.[31]

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[31] Nadine Guthapfel (Mai 2007)

Tab. 12.39 Input used in the evaluated covered biogas plants using trail hose for spreading the digested matter

only covered plants using trail hose	**t FS**	**t TS**	**t OS**	**m3 Biogas /t FM**	**total m3 Biogas**	**Share**
fat & oil	4'477	2'239	2'015	450	2'014'650	54%
cereals	938	750	600	320	300'160	
catering waste	4'837	967	822	136	657'832	23%
Vegetables and organic waste	4'877	683	546	67	327'734	
Sum co-substrate	**15'129**	**4'639**	**3'983**	**973**	**3'300'376**	
manure	49'506			19.8	982'624	23%
Total biogas					**4'283'000**	

Tab. 12.40 Unit process raw data of biogas mix at agricultural co-fermentation, covered

	3702	3703	3706	3707	3708	3709	3792
	Name	Location	Unit	biogas, mix, at agricultural co-fermentation, covered	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			Nm3			
product	biogas, mix, at agricultural co-fermentation, covered	CH	Nm3	1			
technosphere	biogas, from biowaste, at agricultural co-fermentation, covered	CH	Nm3	2.30E-1	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.
	biogas, from fat and oil, at agricultural co-fermentation, covered	CH	Nm3	5.41E-1	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants. In the year 2006 a large amount of fat and oil were used to produce biogas. According to the market situation this can change in the future
	biogas, from slurry, at agricultural co-fermentation, covered	CH	Nm3	2.29E-1	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.

Tab. 12.41 Unit process raw data of biogas mix at agricultural co-fermentation, covered, meta information

ReferenceFuncti on	401	Name	biogas, mix, at agricultural co-fermentation, covered
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	Nm3
DataSetInformatic	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	This process assembles the different processes to produce biogas in a covered agriculotural biogas plant
	404	Amount	1
	490	LocalName	Biogas, Mix, ab landwirtschaftliche Kovergärung, mit Abdeckung
	491	Synonyms	
	492	GeneralComment	The invetory refers to a covered agricultaral biogas plant in Switzerland in the year 2006 with a capacity of $500m^3$ and a life time of 20 years.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2006-01-01
	602	EndDate	2006-12-31
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	20 plants in the year 2006 have been evaluated
Geography	663	Text	This process refers to the situation in Switzerland for this type of plants.
Technology	692	Text	To avoid Methan emissions the new plants in Switzerland are covered, to reduce NH3 emissions the digested matter will be spread with a trail hose.
Representativene	722	Percent	50
	724	ProductionVolume	12 mio. m3 Biogas
	725	SamplingProcedure	The data are the average of 20 plants in Switzerland to produce electricity according the criteria of "naturemade"
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	75
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

12.8 Biogas from Grass

12.8.1 System Characteristics

In order to guarantee the profitability of the biogas generation, the manufacturing of additional products –e.g. in a so-called grass-refinery or bio-refinery – is essential. A bio-refinery is a technical concept for whole crop utilisation. It applies fractionation to separate different quantities from the raw material and thereby aiming to optimise the value added (Grass 2004). In Switzerland, a grass-refinery plant was in operation between January 2001 and summer 2003 in Schaffhausen. A comprehensive grass-refinery process (see Fig. 12.5 for a schematic process flow diagram) was designed to produce three products: biogas, fibres and proteins (Baier & Delavy 2003).

In the below section, potential products and their application are briefly described.

Grass fibres

Grass fibres can be recovered at a length of 2-30 mm. Variation is due to raw material variation and process conditions. Grass fibres are suitable and competitive for short fibre applications. The following products can be made from grass fibres (Grass 2004):

- Insulation products.
    - Insulation boards can be produced in a density range between 60 and 160 kg/m3. The heat conductivity is 0.04-0.045 W/mK, depending on the density of the board. Resistance against fire and fungi can be achieved using additives. Advantages compared with mineral wool include the high specific heat capacity, which results in a 10-12 hours delayed release of outside heat to the inside and improved summer heat protection. Boards can be used for thermal insulation in ventilated facades and cavity masonry, steep-pitched roofs, over rafters and for sound insulation. Possible applications of grass-based insulation boards cover around 80% of all insulation applications.
    - Blow-in insulation is successful at a blow-in density of 55-60 kg/m3. The heat conductivity is 0.04 W/mK. Resistance against fire and fungi can be achieved by using additives. Quality control must include settling properties. Blow-in insulation is an industrial standard in many countries and makes about 1.4% of the total insulation volume in Germany.
- Natural fibre re-enforced plastic: specifications include filling grade and mechanical properties.
- Paper: specifications include colour and mechanical properties.
- Combustion pellets: specifications include mechanical stability, levels of ash, nitrogen, and sulphur content and ash melting point. To reduce the ash content, low or medium-quality grass requires washing.

Grass protein

The value of grass as a ruminant feed is based on its raw protein content. Separation of the protein fraction from the cell wall components opens marketing opportunities for non-ruminants, e.g. pigs and hens. Juice pressed from silage grass has been fed successfully to pigs and piglets. A dried protein product from fresh grass contains around 40% raw protein, 10% raw fat and 15% raw ash, depending on raw material quality and processing conditions. The high methionine content of grass protein makes it particularly suited to laying hens. However, protein extraction and drying are significant cost factors.

Biogas

The water-soluble fraction of good-quality grass yields 200-250 m^3 biogas per tonne of dry matter. Utilisation of biogas includes combustion in a combined heat and power machine, as well as feeding into the natural gas distribution network or gas fuelling stations (after purification and compression).

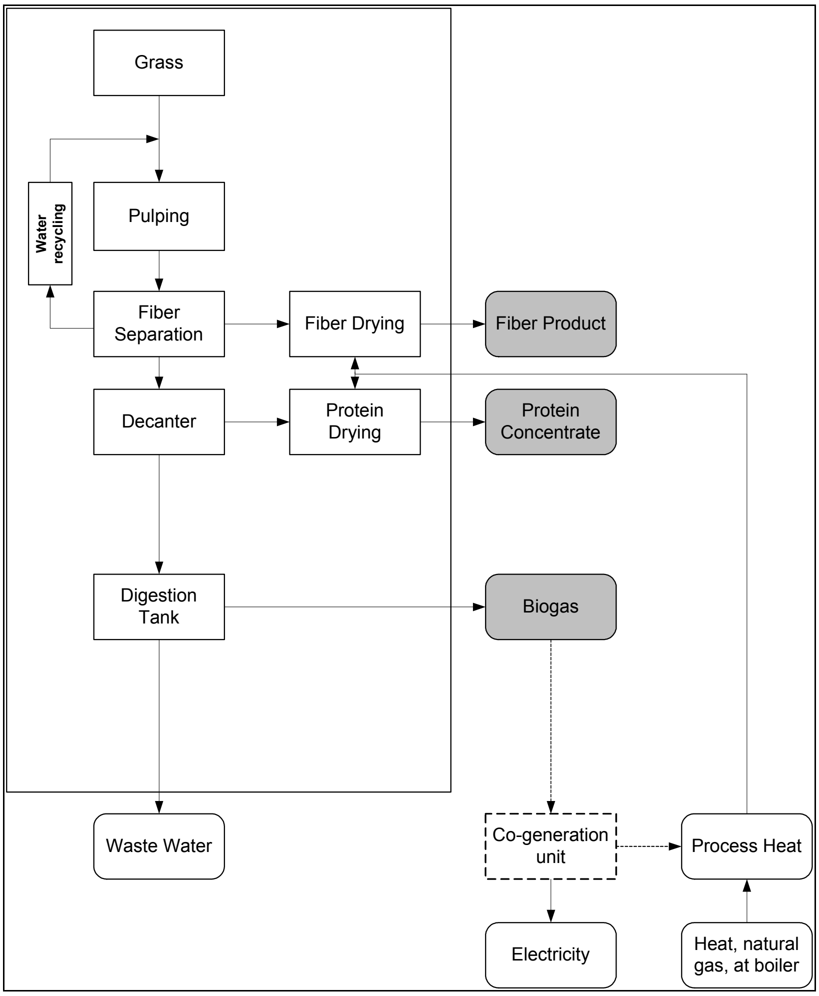

Fig. 12.5 **Schematic process flow sheet for a grass-refinery as modelled in this project. In the white box on the left the processing of grass is illustrated. The grey boxes on the right show the three obtainable products. In this project we assume that the process is optimised to obtain the maximal quantity of biogas as a product. Thus, process energy requirements are covered by using energy from external resources (e.g., required process heat is obtained from combustion of natural gas). At the plant in Schaffhausen, however, heat was obtained from a co-generation unit, as indicated in the sketch with dotted lines.**

The grass-refinery process is designed in such a way that it can be optimised according to specific aims (fractionation). This can be the fibre recovery at a specific length distribution profile, or the extraction of proteins, or the optimised recovery of soluble chemical oxygen demand (COD) for biogas production.

During operation the plant demonstrated the general feasibility of producing technical fibres and biogas (Grass 2004). The technical fibres were further processed on-site for production of a blow-in insulation product. Biogas was utilised in a combined heat and power plant. Heat was used internally for drying fibres. In order to make the entire refinery profitable, it was planned to certify and offer the generated power under the label “Naturemade Star”.

Production of proteins was planned to be added as a further step. The plant, however, was shut down before the required processes for the generation of proteins were implemented. The reasons for shutting down were manifold[32]:

- Technical teething trouble: e.g. the capacity of grass scrubber was not sufficient to cope with unexpected high shares (up to 20%) of polluting materials such as sand and stones. Conse-

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[32] Personal communication with Stefan Grass plant manager of the plant in Schaffhausen

quently the scrubber had to be re-sized and replaced. Also, the actual capacity of the drier did not match its specification.

- Unexpected labour costs due to more staff required for packaging of products.
- Changing business environment: Exit of bank investor
- Decreasing engagement of project promoters

12.8.2 Life Cycle Inventories for Grass Fermentation

In order to account for the fact that the described process produces three products, a multi-output process is set up.

Technical Characteristics

The plant was designed for a raw material throughput capacity around 0.8 tonnes of dry matter per hour. Janzing (2001) reported that a yearly input of 4400 t_{DM} of grass (dry matter) was expected. According to Grass (2004) the yield of technical fibres was 500-600 kg per tonne of dry matter and the biogas yield was 150-250 Nm^3, depending on raw material quality. Additional production volumes are given in Baier (2003) and a confidential LCA study (Carbotech 2000).

In Tab. 12.42 the yields of the three products as reported in different sources are summarised [33].

Tab. 12.42 Possible yields of products generated in a grass-refinery

		Baier 2003 $^{1)}$	Grass 2004 $^{2)}$	Carbotech 2000				
Grass Type		-	-	ballanced rye grass	High Clover	High Rye	Lucern	Oeko-Grass
Fibres	kg/t $grass_{DM}$	**400**	550	405	354	352	474	508
Protein	kg/t $grass_{DM}$	**150**	-	175	175	152	201	181
Biogas	Nm^3/t $grass_{DM}$	**210**	200	301	325	349	220	222

1) Used in this study

2) Fibres: 500-600 kg/$Grass_{DM}$, Biogas 150-250 kg/$Grass_{DM}$, Protein was not produced in the initial period of operation .

Biogas is digested in a digestion tank. In Schaffhausen, an up-flow anaerobic sludge bed (UASB) reactor design for biogas production from the water-soluble extracts of grass has been adapted. This reactor design is widely applied in breweries, the sugar industry and various other industries. High-rate anaerobic reactors, such as UASB reactors offer advantages for soluble substrates and larger-scale applications. They also offer scale-up advantages for bio-refinery systems applying solid/liquid separation.

Raw material input and carbon balance

In line with the production of ethanol from grass (see chapter ”ethanol”) three different types of grass representing the average grass mix of Switzerland are considered. The share of each type is presented in chapter "ethanol". The carbon input is determined by the carbon content of the modelled grass-input (0.45 kg_C/kg_{Grass}). The carbon contents of the generated products are summarised in Tab. 12.43.

The carbon content of the fibres was assumed as 0.44 kg per kg dry matter, and the carbon content of the proteins was calculated as 0.4 kg per kg dry matter (according to Nemecek 2004).

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[33] It should be noted that the characteristics of the delivered grass have an important impact on the yield of the final products. For instance, as a consequence of a late cut, a high fibre yield may be expected. In turn, biogas yields increase, if fresh grass is used.

Tab. 12.43 Carbon content of products and allocation factors grass input

Specific biogas generation	Nm3/Kg$_{grass}$	0.210
C-Content in biogas	Kg$_{C}$/Nm^{3}	0.536
C-Content in biogas generated from 1 kg Grass	Kg$_{C}$/Kg$_{grass}$	0.112
Allocated share of C to biogas		**0.323**
Specific fibre production	kg$_{fibres}$/Kg$_{grass}$	0.400
C-Content in fibres	kg$_{C}$/Kg$_{Fibre}$	0.440
C-Content in fibres generated from 1 kg Grass	Kg$_{C}$/Kg$_{grass}$	0.176
Allocated share of C to fibres		**0.505**
Specific Protein production	kg$_{fibres}$/Kg$_{grass}$	0.150
C-Content in proteins	kg$_{C}$/Kg$_{Protein}$	0.400
C-Content in proteins generated from 1 kg grass	Kg$_{C}$/Kg$_{grass}$	0.060
Allocated share of C to proteins		**0.172**
Total Carbon in all Products generated from 1 kg Grass	Kg$_{C}$/Kg$_{grass}$	**0.348**
Carbon input	Kg$_{C}$/Kg$_{grass}$	0.45
Carbon in wastewater	Kg$_{C}$/Kg$_{grass}$	**0.102**

Ideally, the stored uptake of carbon during grass growing in the plant should equal the biogenic carbon content of the biogas and bio-products. However, as illustrated in Tab. 12.43 the cumulative carbon content of the single products is lower than the carbon input. A correct carbon balance should maintain for the entire process as well as for each product. Thus, in order to maintain the carbon balance the surplus of carbon is accounted for in the composition of the wastewater (see section emissions to water).

Transport

As a first approximation the transport of the grass (small lorry) to the grass-refinery is estimated with a distance of 10 km.

Energy consumption

Heating is required for the pre-treatment of the grass, and post treatment (drying) of fibres and proteins.

We assume that the pre-treatment stage should be the same as for the ethanol production from grass. For ethanol, Fromentin et al. (2000) stated that the steam consumption for the pre-treatment stage is 5.1 MJ/litre of ethanol, and the electricity consumption 0.5 kWh/l (while the consumption of grass is 32.7 kg of fresh grass per litre of ethanol). Based on these figures, we calculate a specific heating value of 0.96 MJ/kg$_{Grass\_DM}$. The allocation to the three products is based on the economic allocation as described below.

As demonstrated in Fig. 12.5 digestion takes place at the end of the refinery process, and hence the input substance (grass juice) has already achieved the required digestion temperature.

For post treatment of proteins and fibres, we assume – according to Carbotech (2000) – a specific heat consumption for fibres drying and protein drying of 2.50 MJ/kg$_{evarporated\ water}$ and 4.01 MJ/ MJ/kg$_{evarporated\ water}$, respectively. In Tab. 12.44 the calculated heating consumption for different grass inputs are summarised.

Tab. 12.44 Heating consumption for drying processes of products (fibres and proteins).

			Ballanced rye grass$^{1)}$	High Clover$^{1)}$	High Rey$^{1)}$	Lucern 4$^{1)}$	Oeko-Grass$^{1)}$	this study$^{2)}$
Fibres	Water-content before drying	kg/$t_{GrassDM}$	520	455	453	609	653	
	Water content after drying	kg/$_{tGrassDM}$	20	18	18	24	25	
	Energy for drying	MJ/$kg_{evaporated\ water}$	2.5	2.5	2.5	2.5	2.5	
	Total energy	MJ/$t_{GrassDM}$	1250	1093	1088	1463	1570	**1236**
	Specific energy for drying	MJ/kg_{Fibres}	3.09	3.09	3.09	3.09	3.09	**3.09**
Proteins	Water-content before drying	kg/$t_{GrassDM}$	350	350	350	350	350	
	Water content after drying	kg/$_{tGrassDM}$	9	9	8	10	9	
	Energy for drying	MJ/$kg_{evaporated\ water}$	4.01	4.01	4.01	4.01	4.01	
	Total energy	MJ/$t_{GrassDM}$	1367	1367	1371	1363	1367	**1170**
	Specific energy for drying	MJ/kg_{Fibres}	7.81	7.81	9.02	6.78	7.55	**7.80**
Process	Total Energy Consumption	MJ/$kg_{GrassDM}$	2.62	2.46	2.46	2.83	2.94	**2.41**

1) water content and specific energy for drying is taken from Carbotech (2000)

2) specific energy consumption for drying is the average of the presented figures in columns 4-8. Total energy values are based on own calculations.

Electricity is required for operation of various devices, such as grass reception belts, hexler, comminutor, fibre press, decanter, fans, blowers, juice recycle pumps, pelletiser. In Carbotech (2000) a total electricity consumption of 205 kWh/$t_{grassDM}$ is reported. It should be noted that in contrast to other digestion processes as described in this chapter, no agitation of the input substance while staying in the biogas reactor is required.

Similar as for bio waste digestion, various concepts of energy supply for the digestion of sewage sludge are possible. In principle, if biogas is used as a fuel for co-generation, the heat expenditures can usually covered completely, and electricity demand can be covered partly by the produced heat and electricity from on-site co-generation. However, this would result in a lower process efficiency of the digestion process; i.e. ideally an adjustment with respect to the final yield of biogas is performed. On the other hand, if biogas is assumed to be used as a feedstock for transportation fuels, the process most likely would be optimised in a way that a maximum yield of biogas is achieved. The reason for this is that a higher biogas throughput in the biogas upgrading plant significantly reduces the cost for the biogas upgrading[34]. In case that all biogas is fed in the upgrading plant, the required heat and electricity is obtained from conventional energy carriers.

The dataset as presented in this study is based on the assumption, that the biogas is upgraded and used as a fuel. For electricity the current Swiss supply mix is employed. For heat supply various options are possible. In this study we assume that the heat demand is covered by natural gas combustion. Alternatively also wood chips may be used.

Emissions to air

According to Baier & Delavy (2003) emissions from the gasholder are fed back to the biogas. Thus, we assume that in the digestion process, storage and transport of biogas no emissions occur. The difference between the carbon content in the three products (biogas, fibres and proteins) and the amount of carbon fixed in the grass input is not accounted for as CO_2-emission but as carbon in wastewater (see next section).

Emissions to water and water input

Although, water is recycled and used within the process, wastewater leaves the process. According to Carbotech (2000). about 3-6 $kg_{wastewater}/kg_{GrassDM}$ will leave the process. In Tab. 12.45 quantities for several grass-inputs are presented. There seems to be a tendency that a high biogas yield goes hand in hand with high wastewater quantities. Thus, for our model – representing a rather low biogas yield – we assume a wastewater quantity of 4.0 $kg_{wastewater}/kg_{GrassDM}$. This results in 25.4 kg TOC per m^3 effluent. A process specific wastewater treatment dataset has been generated to account for the expendi-

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[34] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

tures of wastewater-treatment in general and for the remaining carbon in particular. Based on the assumed quantity of wastewater and the water losses due to drying fibres and proteins (see Tab. 12.44), we account for a total water input of 4.858 $kg_{water, river}/kg_{GrassDM}$.

Tab. 12.45 Wastewater quantities for a grass-refinery

Grass Type		Ballanced Rye Grass	High Clover	High Rye	Lucern	Oeko-Grass	This study
Wastewater	$kg_{wastewater}/kg_{GrassDM}$	3.25	6.02	6.03	3.133	3.09	**4.00**

Infrastructure

For infrastructure expenditures we use the dataset "ethanol fermentation plant" as a first approximation.

Allocation

The allocation for non-carbonaceous exchanges is based on economic revenues of the gained products. Figures for the revenue of biogas are not readily available. The German "Fachverband Bioenergie" suggested a compensation of 5-10 cents/kWh for the feeding of biogas in the gas or electricity network (IWR 2001). Mr. Zeifang from KOMPOGAS reported a quantity of 0.04 CHF/kWh[35]. The later value is used in this study. Figures for protein and fibres are taken from Fromentin et al. (2000). In Tab. 12.46 the employed figures are summarised.

Tab. 12.46 Allocation factors for co-products from the grass-refinery

	Specific Revenue		Quantity			
Product	**Unit**		**Unit**		**Total revenue (CHF/t grass$_{DM}$**	**Allocation Key**
Biogas	CHF/KWh	0.04	Nm3/t grass$_{DM}$	210	46.06	**0.09**
Fibres	CHF/kg	1	kg/t grass$_{DM}$	400	400	**0.75**
Proteins	CHF/kg	0.6	kg/t grass$_{DM}$	150	90	**0.17**

Allocation for heat-consumption is based on product specific treatment consumption and pre-treatment consumption for substrate treatment. Product specific treatment consumption is allocated 100% to the treated product, whilst pre-treatment heating expenditures are allocated according to the values presented in Tab. 12.46. In Tab. 12.47 the resulting overall allocation values for heating consumption are summarised.

Tab. 12.47 Allocation factors for heating expenditures

Product		Product Specific heat	Heat for pre-treatment	Total heat per product	Allocation Factor Heat
Biogas	MJ/kg_{Grass_DM}	0.00	0.08	0.08	0.025
Fibers	MJ/kg_{Grass_DM}	1.24	0.72	1.95	0.580
Proteins	MJ/kg_{Grass_DM}	1.17	0.16	1.33	0.395
Total	MJ/kg_{Grass_DM}	2.41	0.96	3.37	1

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[35] Oral communication with Mr. Zeifang, KOMPOGAS (12.04.2006)

Life cycle inventory data

In Tab. 12.48 the input data for the grass-refinery are presented.

Tab. 12.48 Unit process raw data of a grass-refinery

	Name	Location	Infrastructure Process	Unit	grass, to digestion	UncertaintyType	StandardDeviation95%	GeneralComment	biogas, from grass, digestion, at storage	proteins, from grass, at digestion	grass fibres, at digestion	biogenic carbon content	biogenic carbon balance
	Location				CH				CH	CH	CH		
	InfrastructureProcess				0				0	0	0		
	Unit				kg				Nm3	kg	kg	kg	
allocated products	biogas, from grass, digestion, at storage	CH	0	Nm3	0.2100				100	0	0	0.536	0.1125
	proteins, from grass, at digestion	CH	0	kg	1.50E-1				0	100	-	0.400	6.00E-2
	grass fibres, at digestion	CH	0	kg	4.00E-1				-	0	100	0.440	1.76E-1
technosphere	grass from meadow intensive IP, at field	CH	0	kg	3.240E-01	1	1.12	(2,3,1,1,1,3); literature studies	32.00	17.00	51.00	0.454	0.15
	grass from natural meadow extensive IP, at field	CH	0	kg	6.100E-02	1	1.12	(2,3,1,1,1,3); literature studies	32.00	17.00	51.00	0.453	0.03
	grass from natural meadow intensive IP, at field	CH	0	kg	6.150E-01	1	1.12	(2,3,1,1,1,3); oral communication	32.00	17.00	51.00	0.454	0.28
	ethanol fermentation plant	CH	1	unit	4.950E-11	1	3.07	(3,3,2,3,1,5); own estimate	8.59	16.79	74.62		
	heat, natural gas, at boiler condensing modulating >100kW	RER	0	MJ	3.368E+00	1	1.23	(2,3,2,3,1,5); literature studies and own consumptions	2.45	39.53	58.02		
	electricity, low voltage, at grid	CH	0	kWh	2.050E-01	1	1.23	(2,3,2,3,1,5); literature studies and own consumptions	8.59	16.79	74.62		
	transport, lorry 16t	CH	0	tkm	6.667E-02	1	2.10	(4,5,na,na,na,na); oral communication	8.59	16.79	74.62		
	Water, river	-	-	m3	4.858E-03	1	3.07	(3,3,2,3,1,5); own calculation	8.59	16.79	74.62		
	treatment, sewage grass refinery, to wastewater treatment, class 3	CH	0	m3	4.000E-03	1	1.50	(3,3,2,3,1,5); own estimates based on literature studies	31.08	16.28	52.64		-0.1015
	Heat, waste	-	-	MJ	7.380E-01	1	3.06	(2,3,2,3,1,5); own calculation	8.59	16.79	74.62		
									kg	kg	kg		
	Carbon input			kg					0.1451	0.0771	0.2313		0.4535
	Carbon output (product)			kg					0.1125	0.0600	0.1760		0.3485
	Carbon in wateremissions			kg					0.0327	0.0171	0.0553		0.1051

Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

12.9 Biogas from Whey

12.9.1 System Characteristics

The data presented in this section is based on a recent study on alternative applications of whey from cheese production (Fruteau de Laclos & Membrez 2004). This study contains an LCA on the production of biogas from whey digestion. The yearly production of whey is stated as 2800 m^3. The biogas production is next-door to the diary. Thus, no transport of whey is required. The fermentation of this amount of whey results in a yearly biogas production of 122’550 m^3. Thus, 22.8 kg whey are required for the production of 1 m^3 biogas. Fruteau de Laclos & Membrez (2004) assumed that the biogas is used to generate exclusively heat for the digestion process as well as for the cheese production. However, implementation of a co-generation unit is another option. In this study we assume that both heat and electricity are generated in co-generation of biogas. The presented dataset in this project merely addresses the digestion of whey. The functional unit is the production of 1 Nm^3 biogas from digestion of whey. Similar as for biogas production of sewage sludge and manure, the potential use or treatment of digested matter is outside the system boundaries, and the system is modelled as a single output process. In addition to data presented in Fruteau de Laclos & Membrez (2004), detailed information provided by Arnaud Dauriat (ENERS) is used in the LCI-dataset.

12.9.2 Life Cycle Inventories for Whey Digestion

Raw material input and carbon balance

In Tab. 12.49 the composition of whey and the resulting carbon content are summarised.

Tab. 12.49 Characteristics of the whey composition

	formula [1)]	composition whey [2)]	molecular weight	C-content	C-share
		kg/kg	$kg_{substance}$/kmol	kg_C/kmol	$Kg_C/kg_{substance}$
water	H_2O	0.936	18	0	0.000
lactose	$C_{12}H_{22}O_{11}$	0.049	342	144	0.421
proteins	$C_{5.35}H_{9.85}N_{1.35}O_{2.35}S_{0.15}$	0.008	135.35	64.2	0.474
lipids	$C_{21.58}H_{36.3}O_{2.08}$	0.005	328.54	258.96	0.788
others		0.002			
dry organic substance		0.062			0.458
Total		1			0.028

1: derived from Fruteau de Laclos & Membrez (2004)

Based on theses figures a CO_2 resource consumption of 0.104 kg CO_2/ kg whey is calculated.

Whey is a waste product from the cheese production with no economic value and hence all expenditures for the whey production are allocated to the cheese production. As stated above, cheese production is outside the system boundaries. Thus, the dataset "whey, at dairy" (see Tab. 12.50) merely contains the resource use of carbon dioxide.

Tab. 12.50 Life cycle data for whey, at dairy

	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	whey, at dairy	UncertaintyType	StandardDeviation95%	GeneralComment
	Location						CH			
	InfrastructureProcess						0			
	Unit						kg			
product	whey, at dairy	CH	-	-	0	kg	1.00E+0			
resource	Carbon dioxide, in air	-	resource	in air	-	kg	1.04E-1	1	1.29	(3,4,3,3,1,5); own calculation based on literature studies

Energy consumption, operating supply items and infrastructure

The actual yearly consumption of electricity and heat is available from Fruteau de Laclos & Membrez (2004). Additional data of operating supply items was delivered by Arnaud Dauriat (ENERS). For infrastructure expenditures, we use the dataset "anaerobic digestion plant, agricultural waste" as a first approximation.

Wastewater Treatment

According to Fruteau de Laclos & Membrez (2004) a use of digested matter for pig feedings is not possible. In this research we assume that the process waste is treated in a wastewater treatment plant. Data of the composition of digestion process wastewater was provided by Arnaud Dauriat (ENERS). A process specific wastewater treatment dataset has been generated to account for the expenditures of wastewater-treatment in general and for the remaining carbon in particular. The employed input data is summarised in Tab. 12.51.

Tab. 12.51 Composition of whey digestion wastewater

Substance	Unit	Value
Chemical Oxygen Demand COD	[kg/m3]	11.7
Biological Oxygen Demand BOD5	[kg/m3]	7.8
Dissolved organic carbon DOC as C	[kg/m3]	5.1
Total organic carbon TOC as C	[kg/m3]	5.1
Total Nitrogen N-tot. as N	[kg/m3]	0.9
Total P-tot. as P	[kg/m3]	0.3
Calcium Ca	[kg/m3]	0.9
Potassium K	[kg/m3]	1.8

Life cycle inventory input data

In Tab. 12.52 the input data for whey digestion are presented

Tab. 12.52 Life cycle data of the digestion of whey

	Name	Location	InfrastructureProcess	Unit	biogas, from whey, digestion, at storage	UncertaintyType	StandardDeviation95%	GeneralComment	biogenic carbon content	biogenic carbon balance
	Location				CH					
	InfrastructureProcess				0					
	Unit				Nm3				%	
product	biogas, from whey, digestion, at storage	CH	0	Nm3	1.00000E+00					
technosphere	whey, at dairy	CH	0	kg	2.30000E+01	1	1.60	(3,4,2,1,4,5); literature studies and own calculations	0.27	0.652
	heat, at cogen with biogas engine, allocation exergy	CH	0	MJ	1.57160E+00	1	1.60	(3,4,2,1,4,5); literature studies and own calculations		
	electricity, at cogen with biogas engine, allocation exergy	CH	0	kWh	8.57609E-02	1	1.60	(3,4,2,1,4,5); literature studies and own calculations		
	anaerobic digestion plant, agriculture	CH	1	unit	7.68049E-07	1	3.55	(5,5,2,1,4,5); data from digestion of manure used as first approximation		
	treatment, sewage whey digestion, to wastewater treatment, class 4	CH	0	m3	2.28478E-02	1	1.25	(2,4,2,3,1,5); specific dataset for whey wastewater treatment		0.117
	soda, powder, at plant	RER	0	kg	6.85435E-02	1	1.60	(3,4,2,1,4,5); case specific data, provided in oral communication		
	retention aids, in paper production, at plant	RER	0	kg	1.14239E-03	1	1.60	(3,4,2,1,4,5); case specific data, provided in oral communication		
	transport, lorry 16t	CH	0	tkm	2.31563E-03	1	2.30	(3,4,2,1,4,5); case specific data, provided in oral communication		
	transport, lorry 28t	CH	0	tkm	2.31563E-03	1	2.30	(3,4,2,1,4,5); case specific data, provided in oral communication		
	transport, freight, rail	CH	0	tkm	9.26251E-03	1	2.30	(3,4,2,1,4,5); case specific data, provided in oral communication		
	Heat, waste	-	-	MJ	3.08739E-01	1	1.09	(2,1,1,3,1,3); own calculations		
carbon balance	Carbon input			kg						0.652
	Carbon output (biogas)			kg						0.536
	Carbon wastewater			kg						0.117

12.10 Summary of Key Factors

In the below table, the key parameters for the modelled digestion processes are summarised.

Tab. 12.53 Summary of key parameters for various digestion processes

Substrate		Biowaste	Sewage Sludge	Manure	Manure and Biowaste	Grass 1)	Whey 2)
Digestion Process		Thermophile Dry Fermentation (55°C)	Mesophil Fermentation (35°C)	Mesophil Fermentation (35°C)	Mesophil Fermentation (35°C)	Mesophil Fermentation (35°C) (UASB-reactor)	Mesophil Fermentation (35°C)
Substrate Input	kg/Nm^3 biogas	10				4.8	
	m^3/Nm^3 biogas		0.060	0.048	0.038		0.023
Process Yield	Nm^3 biogas/ kg Substrate	0.1				0.21	
	Nm^3 biogas/ m^3 Substrate		16.67	20.73	26.32		43.48
Plant Lifetime	years	25	30	20	20	20	20
Mass-(Substrate) Flow	t/a	10000				4672	
	t/d	27.40				12.8	
	m3/a		54750	3128	3909	n.a	2800
	m3/d		150	8.6	10.7	n.a	8
Retention Time Fermerter	days	14	30	28	28	n.a	n.a
Biogas Production	Nm^3/year	1.00E+06	9.13E+05	6.50E+04	1.04E+05	n.a	1.23E+05
	Nm^3/day	2740	2500	178	284	2688	337
Heat (allocated to Biogas)	MJ/Nm^3 biogas	1.08	4.02	7.9	4.96	0.40	1.6
Electricity (allocated to Biogas)	kWh/Nm^3 biogas	0.07296	0.25	0.15	0.15	0.18	0.01
Allocation Factor Energy Input		0.1824	n.r.	n.r.	n.r.	0.025	n.r.
Heat (Total Process)	MJ/Mg Substrate Input	594	n.r.	n.r.	n.r.	3370	n.r.
Eelctricty (Total Process)	kWh/Mg Substrate Input	40	n.r.	n.r.	n.r.	205	n.r.

n.r.: not relevant

n.a. not available

1) Substrate input, process yield and energy use (heat & electricity) refer to fresh matter. The remaining figures represent the upper limit for dry matter.

2) Data for plant life time are taken from manure digestion as a first approximation

12.11 Cumulative Results and Interpretation

12.11.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

12.11.2 Cumulative Results of Biogas Plant Infrastructure

The below table shows the selected LCI results and the cumulative energy demand for biogas plant infrastructure.

Tab. 12.54 Selected LCI results and the cumulative energy demand for biogas plant infrastructure

		Name		anaerobic digestion plant, agriculture	anaerobic digestion plant, biowaste	anaerobic digestion plant, sewage sludge
		Location		CH	CH	CH
		Unit	Unit	unit	unit	unit
		Infrastructure		1	1	1
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.79E+05	1.23E+07	1.45E+06
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	5.80E+04	1.68E+06	2.21E+05
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.92E+04	4.85E+05	7.38E+04
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.03E+03	3.01E+04	3.55E+03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	3.41E+03	8.65E+04	1.21E+04
LCI results						
resource	Land occupation	total	m2a	4.2E+3	1.4E+5	8.6E+4
air	Carbon dioxide, fossil	total	kg	3.7E+4	9.8E+5	1.6E+5
air	NMVOC	total	kg	2.3E+1	6.9E+2	9.5E+1
air	Nitrogen oxides	total	kg	1.1E+2	3.3E+3	4.7E+2
air	Sulphur dioxide	total	kg	6.4E+1	1.9E+3	2.0E+2
air	Particulates, < 2.5 um	total	kg	2.1E+1	5.2E+2	7.7E+1
water	BOD	total	kg	1.1E+2	4.4E+3	3.9E+2
soil	Cadmium	total	kg	2.7E-5	1.0E-3	1.3E-4
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	8.7E+2	5.3E+3	1.4E+3
air	Carbon dioxide, land transformation	low population density	kg	7.8E-2	2.4E+0	3.6E-1
air	Methane, biogenic	total	kg	4.0E-2	1.2E+0	1.4E-1
air	Carbon monoxide, biogenic	total	kg	5.8E-1	7.8E+1	1.9E+0

The cumulative emission scores reflect the difference in plant size: Highest cumulative scores are revealed for the bio waste plant, whilst the agricultural biogas plant shows lowest emissions. The selected results for the infrastructure of the biogas plant with coverage to reduce methane emission is not given in the table Tab. 12.54 because there are nearly no differences to the other plant without coverage. The only differences are the size leading in a scaling factor of 1.66 and a small amount of rubber to cover the storage, see chapter 12.7.2.

12.11.3 Cumulative Results for the Fermentation Processes

The below table shows the selected LCI results and the cumulative energy demand for various fermentation processes investigated in this project.

Tab. 12.55 Selected LCI results and the cumulative energy demand for various digestion processes

Name			Biogas, from agricultural co-digestion, not covered, at storage	Biogas, from agricultural digestion, not covered, at storage	Biogas, from biowaste, at storage	Biogas, from grass, digestion, at storage	Biogas, from sewage sludge, at storage	Biogas, from whey, digestion, at storage
location			CH	CH	CH	CH	CH	CH
Unit			m3	m3	m3	m3	m3	m3
Infrastructure			0	0	0	0	0	0
energy ressources								
non-renewable								
fossil		MJ Eq	1.1E+0	1.0E+0	1.8E+0	2.4E+0	5.1E+0	2.0E+0
nuclear		MJ Eq	5.4E-1	5.9E-1	5.6E-1	1.8E+0	1.9E+0	1.7E+0
renewable		MJ						
biomass		MJ Eq	6.1E-3	7.0E-3	5.0E-3	2.7E+1	1.5E-2	4.1E-2
wind, solar, geothermal		MJ Eq	2.3E-3	2.6E-3	2.1E-3	6.7E-3	6.6E-3	1.1E-2
water		MJ Eq	4.1E-3	6.1E-3	1.1E-3	3.8E-3	1.7E-3	1.3E-2
selected LCI results								
NMVOC	air	kg	9.7E-5	9.1E-5	1.1E-4	1.9E-4	1.2E-4	8.3E-5
CO2, fossil	air	kg	8.3E-2	8.9E-2	1.2E-1	1.5E-1	2.9E-1	1.5E-1
sulphur dioxide	air	kg	2.1E-4	2.7E-4	8.4E-5	2.3E-4	1.7E-4	4.8E-4
nitrogen oxides	air	kg	6.6E-4	6.8E-4	2.5E-4	1.0E-3	2.1E-4	9.1E-4
particulates >10 um	air	kg	4.7E-5	6.1E-5	2.7E-5	8.0E-5	3.6E-5	1.4E-4
particulates, >2.5 um and <10	air	kg	2.8E-5	3.7E-5	1.4E-5	4.0E-5	1.2E-5	6.8E-5
particulates, <2.5 um	air	kg	2.7E-5	2.9E-5	1.9E-5	9.9E-5	1.3E-5	5.2E-5
Ammonia	air	kg	7.3E-3	7.7E-3	4.2E-4	7.4E-3	1.5E-6	4.9E-4
land occupation	ressource	m2a	3.0E-3	4.0E-3	1.5E-3	1.4E+0	4.4E-3	1.0E-2
cadmium	soil	kg	5.0E-11	1.3E-11	1.5E-11	-1.2E-7	2.1E-11	1.3E-10
BOD	water	kg	1.7E-4	1.6E-4	1.9E-4	2.3E-2	4.4E-5	1.7E-2
further LCI results								
N20	air	kg	1.6E-5	2.2E-5	1.8E-4	6.2E-4	4.9E-6	1.3E-4
methane	air	kg	3.1E-2	3.5E-2	1.6E-2	1.4E-3	4.1E-3	1.5E-3
carbon monoxide	air	kg	7.1E-4	9.5E-4	1.5E-4	7.7E-4	1.2E-4	7.3E-4
carbon, biogenic, fixed	air	kg	5.3E-1	5.3E-1	5.3E-1	5.8E-1	5.2E-1	5.7E-1
heat, waste	total	MJ	8.7E+0	1.3E+1	2.4E+0	8.2E+0	7.4E+0	8.9E+0

Biogas derived from digestion of grass shows the highest scores for most presented non-biogenic emissions and for land occupation. In most cases it is the grass supply chain that dominates the emission scores. This result reflects the fact that grass is the only input substrate which is not modelled as a by-product, but as a raw material with allocated environmental burdens in the substrate generation. In addition, the obtained process wastewater and subsequent water treatment dominate or significantly contribute to BOD-emissions and SO_2-emissions of biogas from grass, respectively.

For input substrates such as raw sewage sludge, manure and whey all environmental burdens are allocated to other products and services and hence the raw material input is characterised by zero environmental burdens. The high fossil CO_2-emissions from sewage sludge are a result of the assumed heating with natural gas. High biogenic CO_2-emissions are caused by excess-gas burning ($CH_4 \rightarrow CO_2$). For biogas from manure, plant infrastructure shows considerably contributions to the final score, e.g. 35% and 20% for fossil CO_2 and NMHC, respectively.

The agricultural biogas plants show relatively high emissions of methane and Ammonia compared to the other biogas production. The methane is emitted during the storage of the digested matter. Newer plants have covered stocks to avoid methane emissions. The results for these plants are given in the following table. Another development of the last years concerns the spreading of the digested matter with trail hose to reduce ammonia emissions. The results of these productions are also given in Tab. 12.56. The evaluated covered plants as described in chapter 12.7.4 differ from the older plats without coverage not only by the fact that the methane will be recovered. All these new plants fulfil the standard to produce electricity according to naturemade star. So for example the digested matter has to be spread with trail hose. Other differences concern the digested material. The comparison between Tab. 12.55 and Tab. 12.56 shows a reduction in energy use and especially in the emissions of methane, carbon monoxide and ammonia per m^3 of produced biogas.

Tab. 12.56 Selected LCI results and the cumulative energy demand for biogas from covered plants

Name			Biogas, from biowaste, at agricultural co-fermentation, covered	Biogas, from fat and oil, at agricultural co-fermentation, covered	Biogas, from slurry, at agricultural co-fermentation, covered	Biogas, mix, at agricultural co-fermentation, covered	Application, digested matter from biowaste in agricultural co-digestion, covered
location			CH	CH	CH	CH	CH
Unit			m3	m3	m3	m3	kg
Infrastructure			0	0	0	0	0
energy ressources							
non-renewable							
fossil		MJ Eq	3.6E-1	4.4E-1	4.3E-1	4.2E-1	
nuclear		MJ Eq	2.9E-1	4.3E-1	5.9E-1	4.3E-1	
renewable		MJ					
biomass		MJ Eq	1.7E-1	1.5E-1	1.8E-1	1.6E-1	
wind, solar, geothermal		MJ Eq	1.3E-3	1.8E-3	2.4E-3	1.8E-3	
water		MJ Eq	1.9E-3	1.8E-3	2.2E-3	1.9E-3	
selected LCI results							
NMVOC	air	kg	3.3E-5	4.0E-5	3.8E-5	3.8E-5	0
CO2, fossil	air	kg	2.8E-2	3.3E-2	3.4E-2	3.2E-2	0
sulphur dioxide	air	kg	8.4E-5	1.1E-4	1.4E-4	1.1E-4	0
nitrogen oxides	air	kg	1.5E-4	2.0E-4	1.9E-4	1.9E-4	0
particulates >10 um	air	kg	2.3E-5	2.5E-5	2.9E-5	2.5E-5	0
particulates, >2.5 um and <10	air	kg	1.4E-5	1.4E-5	1.6E-5	1.4E-5	0
particulates, <2.5 um	air	kg	1.3E-5	1.4E-5	1.4E-5	1.4E-5	0
Ammonia	air	kg	2.7E-3	1.8E-4	6.8E-3	2.3E-3	1.3E-4
land occupation	ressource	m2a	4.6E-2	4.1E-2	4.8E-2	4.4E-2	0
cadmium	soil	kg	8.1E-11	8.0E-11	8.1E-11	8.1E-11	6.1E-8
BOD	water	kg	4.8E-5	5.9E-5	5.3E-5	5.5E-5	0
further LCI results							
N20	air	kg	8.3E-4	6.2E-5	2.1E-3	7.1E-4	4.2E-5
methane	air	kg	2.5E-3	4.4E-3	5.4E-3	4.2E-3	0
carbon monoxide	air	kg	2.1E-4	2.7E-4	3.3E-4	2.7E-4	0
carbon, biogenic, fixed	air	kg	5.3E-1	5.3E-1	5.3E-1	5.3E-1	1.0E-1
heat, waste	total	MJ	3.3E+0	5.0E+0	6.9E+0	5.0E+0	0

There are some differences resulting from the different input. For the most results shown in the table the differences are quit small, 10% to 30%. Larger differences occur in the emission of N_2O and Ammonia from fat & oil digestion. These emissions are lower because the input contains only very small amounts of nitrogen. As described in chapter 12.7.4 it is important to note of the fact, that it is not possible to digest fat & oil or catering waste alone.

The results from the disposal of bio waste and fat & oil into agricultural co-fermentation in Tab. 12.57 are comparable to the results for biogas, because these processes are by products of the biogas production.

Tab. 12.57 Selected LCI results and the cumulative energy demand for disposal of biowaste and fat & oil into agricultural digestion plants

Name			Disposal, biowaste, to agricultural co-fermentation, covered	Disposal, biowaste, to anaerobic digestion	Disposal, fat and oil, to agricultural co-fermentation, covered
location			CH	CH	CH
Unit			kg	kg	kg
Infrastructure			0	0	0
energy ressources					
non-renewable					
fossil		MJ Eq	2.4E-2	8.7E-1	2.9E-2
nuclear		MJ Eq	3.2E-2	2.6E-1	3.9E-2
renewable		MJ			
biomass		MJ Eq	1.2E-3	2.8E-3	1.5E-3
wind, solar, geothermal		MJ Eq	1.1E-4	9.9E-4	1.4E-4
water		MJ Eq	3.2E-5	5.5E-4	4.0E-5
selected LCI results					
NMVOC	air	kg	2.1E-6	5.6E-5	2.6E-6
CO2, fossil	air	kg	1.6E-3	5.6E-2	2.0E-3
sulphur dioxide	air	kg	7.1E-6	4.2E-5	8.7E-6
nitrogen oxides	air	kg	1.3E-5	1.4E-4	1.6E-5
particulates >10 um	air	kg	8.3E-7	1.4E-5	1.0E-6
particulates, >2.5 um and <10	air	kg	3.5E-7	7.1E-6	4.3E-7
particulates, <2.5 um	air	kg	4.8E-7	1.1E-5	5.9E-7
Ammonia	air	kg	3.3E-4	2.3E-4	1.7E-5
land occupation	ressource	m2a	3.0E-4	9.0E-4	3.6E-4
cadmium	soil	kg	4.3E-8	4.3E-8	2.2E-12
BOD	water	kg	3.2E-6	9.6E-5	4.0E-6
further LCI results					
N20	air	kg	1.0E-4	8.3E-5	6.0E-6
methane	air	kg	3.0E-4	7.1E-3	4.2E-4
carbon monoxide	air	kg	1.6E-5	7.9E-5	1.9E-5
carbon, biogenic, fixed	air	kg	-1.6E-1	-1.6E-1	-2.4E-1
heat, waste	total	MJ	3.8E-1	1.2E+0	4.7E-1

12.12 Conclusions

The data availability and quality for various digestion processes differs considerably. Data for biowaste, raw sewage sludge and manure digestion is partly based on measurements performed at plants for which technical and economical feasibility has been demonstrated. In contrast, the life cycle inventories for grass digestion and whey may be considered as a first approximation. Further data analysis, for instant sensitivity analysis, is required to draw final conclusions and allow for a comprehensive comparison of the modelled digestion processes.

Interesting are the new developments in agricultural digestion plants. With the covering of the stock and the spreading of the digested matter with trail hoses the emissions of methane and ammonia can be reduced by about 80%.

Abbreviations

CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
DM	dry matter
FM	fresh matter
H_2	hydrogen gas
H_2O	water
H_2S	hydrogen sulphide, also often referred to as sewer gas

HV	heating value
HHV	higher heating value
kWh	kilowatt-hour
LCI	life cycle inventory
LCIA	life cycle inventory assessment
LHV	lower heating value
LU	livestock unit
N_2	nitrogen gas
NH_3	ammonia gas
Nm^3	normal cubic meter
NO_x	nitrogen oxides
O_2	oxygen gas
OS	organic substance
ppm	parts-per-million
SO_x	sulphur oxides
Vol. %	percentage volume (equivalent to percentage molar when dealing with gases)
WWTP	waste water treatment plant

Tab. A. 8 Biowaste Plant

ReferenceFunction	401	Name	anaerobic digestion plant, biowaste
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	1
ReferenceFunctio	403	Unit	unit
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Infrastructure for the pre-treatment process, digestion of bio-waste and the succsesive treatment of the fermented material (de-watering and post composting).
	404	Amount	1
	490	LocalName	Biogasanlage, Kompostvergärung
	491	Synonyms	
	492	GeneralComment	Infrastructure expenditures are recorded for a plant with a yearly capacity of 10'000t and a lifetime of 25 years. For stationary machines a lifetime of 10 years is assumed. As a first approximation, cast iron is assumed as machinery material.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2000
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Data is obtained from a recent LCA study.
Geography	663	Text	Data represents a Swiss plant.
Technology	692	Text	Thermophile, single stage digestion with post composting.
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 9 Biowaste Digestion

ReferenceFunction	401	Name	biowaste, to anaerobic digestion
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the environmental exchanges due to biowaste pre treatment (inclusive the disposal of contaminants) biowaste digestion and post-composting of digested matter. In addition emissions to soil due to the use of presswater and digested matter as a fertiliser in agriculture are recorded. Spreading of the fertilser as well as transport from biowaste plant to farms are taken into account. Gas purification and the use of the gas for co-generation are not included. Biowaste contains biogenous houshold waste, yard waste and food waste.
	404	Amount	1
	490	LocalName	Bioabfall, in Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput process "biowaste to anaerobic digestion " delivers three co-products/services: biogas, disposal of biowaste and application of digested matter as a fertiliser in agriculture. The process is modelled in a way that a maximum amount of biogas is obtained. Allocation for operation expenditures and emissions to air occurring at the biowaste treatment plant has been performed by taking into account the revenues of a plant with a yearly treatment capacity of 10'000 tonnes of biowaste. The above exchanges are allocated as follows: 18% biogas production and 82% waste disposal. For heavy metals and emissions of trace elements to soil a practical allocation has been performed: 50% of the latter are assigned to the disposal service and the remaining 50% are allocated to the application of presswater and digested matter in agriculture. Biowaste input is assumed to have a share of dry matter of 40%, and an organic share of dry matter of 77% with a carbon content of 53%. The share of carbon decomposition during digestion is 76%. Transport processes are only accounted for household biowaste.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1999
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Methane and N2O are based on old measurements.
Geography	663	Text	Conditions of plants in the Canton Zürich
Technology	692	Text	Thermophile, single stage digestion with post composting.
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 10 Sewage Gas Plant

ReferenceFunction	401	Name	anaerobic digestion plant, sewage sludge
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	1
ReferenceFunctio	403	Unit	unit
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Infrastructure of the anaerobic sludge treatment in a wastewater treatment plant. Data includes exclusively the infrastructure of the digestion tank and gasholder. Land occupation and land transformation are included, too.
	404	Amount	1
	490	LocalName	Biogasanlage, Schlammbehandlung
	491	Synonyms	
	492	GeneralComment	Infrastructure is accounted for with a lifetime of 30 years. For stationary machines a lifetime of 10 years is assumed.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2002
	602	EndDate	2002
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Data is obtained from a recent LCA study.
Geography	663	Text	Estimate for Swiss plants.
Technology	692	Text	Swiss average technology. Data refers to an annual treatment of 100'000 PCE
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 11 Sewage Sludge Digestion

ReferenceFunction	401	Name	biogas, from sewage sludge, at storage
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the environmental exchanges due to raw sludge digestion and gas storage. Emissions due to the disposal of sludge are not accounted for. Also, gas purification and the use of the gas for co-generation are not included.
	404	Amount	1
	490	LocalName	Biogas, aus Klärschlamm, ab Speicher
	491	Synonyms	
	492	GeneralComment	The process is modelled in a way that a maximum amount of biogas is obtained. Raw sludge is assumed to have a share of dry matter of 4-6%. Raw sludge digestion fulfils only onefunctions: production of biogas (sewage gas).
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Data represents conditions of large plants in Switzerland
Technology	692	Text	anaerob-mesophile digestion (35 C)
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 12 gricultural Fermentation Plant

ReferenceFunction	401	Name	anaerobic digestion plant, agriculture
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	1
ReferenceFunctio	403	Unit	unit
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Infrastructure for the pre-treatment process, digestion of liquid manure and the succsesive storage of the digested manure. Disposal of plastic and wood are accounted for. In contrast, for disposal of metals cut off allocation is applied.
	404	Amount	1
	490	LocalName	Biogasanlage, Landwirtschaft
	491	Synonyms	
	492	GeneralComment	Infrastructure is accounted for with a lifetime of 20 years. For stationary machines a lifetime of 10 years is assumed. The dump is 90 m^3 and the fermenter (digestion facility) has a capacity of about 300 m^3. The digested manure is stored in two storage tanks with a capacity of 410 or 450 m3.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2005
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Data is obtained from a recent LCA study.
Geography	663	Text	Data represents a Swiss plant.
Technology	692	Text	Typical Swiss plant with a concrete fermentation system
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 13 Anaerobic Digestion of Liquid Manure

ReferenceFunction	401	Name	biogas, from agricultural digestion, at storage
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the in- and outpust due to liquid manure pre treatment, digestion and emissions due to the storage of digested manure that occur as a consequence of the anaerobic treatment of manure . Gas purification and the use of the gas for co-generation are not included.
	404	Amount	1
	490	LocalName	Biogas, aus landwirtschaftlicher Vergärung, ab Speicher
	491	Synonyms	
	492	GeneralComment	The data represent a mixed manure (50% cattle and 50% swines). Liquid manure input is assumed to have a share of dry matter of 7.5%, and an organic share of dry matter of 80% with a carbon content of 50%. All emissions are exclusively allocated to the installation and operation of the agricultural biogas generation.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1999
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Conditions of typical swiss plant.
Technology	692	Text	Mesophile digestion
Representativene	722	Percent	100
	724	ProductionVolume	65097 m^3/a
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 14 Anaerobic Digestion of Liquid Manure and Co-substrate

ReferenceFunction	401	Name	biogas, from agricultural co-digestion, at storage
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the in- and outputs due to liquid manure and co-substrate pre treatment, digestion and storage of digested manure . Also the transport of the co-substrate is taken into account. Gas purification and the use of the gas for co-generation are not included.
	404	Amount	1
	490	LocalName	Biogas, aus landwirtschaftlicher Vergärung und Kossubstrat, ab Speicher
	491	Synonyms	
	492	GeneralComment	The data represent a mixed manure (50% cattle and 50% swines) digested with a cosubstrate. The co-substrate accounts for 20% of the total input. As a first approximation we assume that the co-substrate is identical with average biowaste. Liquid manure input is assumed to have a share of dry matter of 7.5%, and an organic share of dry matter of 80% with a carbon content of 50%. All emissions are exclusively allocated to the installation and operation of the agricultural biogas generation exclusively.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1999
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Conditions of typical swiss plant.
Technology	692	Text	Mesophile digestion
Representativene	722	Percent	100
	724	ProductionVolume	103787 m^3/a
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 15 Anaerobic Digestion of Grass

ReferenceFunction	401	Name	grass, to digestion
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the environmental exchanges due to grass processing in a grass-refinery. Grass-digestion as well as production of fibres and proteins are included. Gas purification and the use of the gas for co-generation are not included. The required process energy (heat for grass-pre-treatment and drying of fibres and proteins and electricity for fibre presses, fans, blowers reception bells etc.) is obtained from conventional energy carriers and not from the use of biogas. Transport of grass to the plant is accounted for (10km). For infrastructure expenditures, the same infrastructure as for bio-ethanol production from grass is used as a first approximation.
	404	Amount	1
	490	LocalName	Gras, in anaerobe Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput process "grass to digestion" describes a bio-refinery (grass-refinery) that delivers three co-products: biogas, proteins and fibres. Allocation for operation expenditures and emissions caused by the processing of grass has been performed by taking into account the revenues of the products. The above exchanges are allocated as follows: biogas: 16; fibre production: 69% and protein production: 15%. Grass input is assumed to have a carbon content of 45%. Allocation for grassinput to the 3 products is based on the carbon content of the products. Biogas: 32%; fibre production: 51% and protein production: 17%. Allocation for heat-consumption is based on product specific treatment consumption and pre-treatment consumption for substrate treatment. Product specific treatment consumption is allocated 100% to the treated product, whilst pre-treatment heating expenditures are allocated to all products applying economic allocation.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2003
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Conditions of plants in Schaffhausen (CH)
Technology	692	Text	Grass-refinery Up-flow anaerobic sludge bed (UASB) reactor design for biogas production
Representativene	722	Percent	100
	724	ProductionVolume	max. 0.8t grass(DM)/d
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 16 Whey, at dairy

Type	ID	Field name, IndexNumber	6323
ReferenceFunction	401	Name	whey, at dairy
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	This process only contains a credit entry accounting for the extraction of CO_2 from atmosphere.
	404	Amount	1
	490	LocalName	Molke, ab Meierei
	491	Synonyms	
	492	GeneralComment	The following composition of whey is assumed: water (93.6 %), lactose (4.9 %), proteins (0.8), lipids (0.5 %), other (0.2 %)
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	production
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Bereitstellung
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2000
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Swiss conditions.
Technology	692	Text	not specified
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 17 Anaerobic Digestion of Whey

Type	ID	Field name, IndexNumber	6422
ReferenceFunction	401	Name	biogas, from whey, digestion, at storage
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the environmental exchanges due to the digestion of whey. Emissions due to gas purification and the use of the gas for co-generation are not included. Digested matter is treated in a wastewater treatment plant.
	404	Amount	1
	490	LocalName	Biogas, aus Molke, anaerobe Vergärung, ab Speicher
	491	Synonyms	
	492	GeneralComment	The yearly production of whey is 2800 m^3. The fermentation of this amount results in a yearly biogas production of 122550 m3. Thus, 22.8 kg whey are required for the production of 1 m3 biogas. Whey digestion fulfils only one functions: production of biogas.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	Data represents conditions in Switzerland
Technology	692	Text	no information available
Representativene	722	Percent	100
	724	ProductionVolume	122550 m3 biogas per year
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

References

AWEL 1998	AWEL (1998) Optimierung der Kehrrichtlogistik in der Gemeinde, ein Leitfaden für die Gemeinden des Kanton Zürich. Amt für Abfall, Wasser, Energie und Luft, Zürich.
Baier & Delavy 2003	Baier U. and Delavy P. (2003) Bioenergie, Protein & Fasern aus Gras. Monitoring des Biogasprozesses. Bundesamt für Energie, Bern.

Baserga 2000	Baserga Urs (2000) Vergärung organischer Reststoffe in landwirtschaftlichen Biogasanlagen, FAT-Bericht Nr. 546/2000, Tänikon
Berglund 2006	Berglund Maria (2006) Biogas Production from a Systems Analytical Perspective, Dissertation an der Universität von Lund, 2006
Betsche 1999	Forschungsergebnisse am Institut für Biochemie von Getreide und Kartoffel, http://www.bagkf.de/JBBAGKF/DDD/JAHRESBERICHTBAGKF1999INST2-99.pdf
BFE 2003	BFE (2003) Schweizerische Statistik erneuerbarer Energieträger. Teilstatistik Biogas 2002. Bundesamt für Energie, Bern, retrieved from: http://www.energie-schweiz.ch/.
BFE 2004	BFE (2004) Potentiale zur energetischen Nutzung von Biomasse in der Schweiz (Anhang). Bundesamt für Energie BFE, Bern.
Carbotech 2000	Carbotech (2000) Beurteilung der Herstellung von Strom, Fasern und Protein aus Gras. Studie zur ermittlung der Umweltauswirkungen. Datasheets, Basel.
Clemens 2006	Joachim Clemens, Manfred Trimborn, Peter Weiland, Barbara Amon (2006) Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. In: Agriculture, Ecosystems and Environment 112 (2006) p. 171–177
Doka 2003	Doka G. (2003) Life Cycle Inventories of Waste Treatment Services. Final report ecoinvent 2000 No. 13. EMPA St. Gallen, Swiss Centre for Life Cycle Inventories, Duebendorf, CH, retrieved from: www.ecoinvent.ch.
Edelmann 2001	Edelmann W., Schleiss K., Engeli H. and Baier U. (2001) Ökobilanz der Stromgewinnung aus landwirtschaftlichem Biogas - Schlussbericht 2001. Arbi Bioenergy GmBH, Baar.
Edelmann 2004	Edelmann W., Baier U. and Engeli H. (2004) Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes and of agricultural wastes. In proceedings from: 10th World Congress on Anaerobic Digestion, AD 2004 Montreal Canada, 29.8.-2.9.2004, Montreal Canada, 29.8.-2.9.2004, retrieved from: http://www.arbi.ch/seite11.htm.
FNR, 2005	Fachagentur Nachwachsende Rohstoffe e.V. (FNR),Gülzow, D (2005) Basisdaten Biogas Deutschland
Fromentin et al. 2000	Fromentin A., Biollay F., Dauriat H., Luca.Porta H., Marchand J.-D. and Sarlos G. (2000) Caractérisation de filières de production de bioéthanol dans le contexte helvétique. Sur mandat de l'Office fédéral de l'énergie, rapport final.
Fruteau de Laclos & Membrez 2004	Fruteau de Laclos H. and Membrez Y. (2004) Energie à partir de petit-lait: Comparaison des filières biogaz et bioéthanol. Bundesamt für Energie (BfE), Bern.
Grass 2004	Grass S. (2004) Utilisation of Grass for Production of Fibres, Proteins and Energy. In: Biomass and Agriculture: Sustainability, Markets and Policies (Ed. OECD). pp. 169-177. OECD Publication Service, Paris retrieved from: www.oecd.org/agr/env.
Gronauer 1997	Gronauer A., Helm M. and Schön H. (1997) Verfahren und Konzepte der Bioabfallkompostierung - Vergleich - Bewertung - Empfehlung. Bayrische Landesanstalt für Landtechnik der TU München-Weihenstestephan.
IWR 2001	IWR (2001) IWR News: Fachverband Biogas fordert Gaseinspeisungsgesetz retrieved from: http://www.iwr.de/news.php?id=610.

Janzing 2001	Janzing B. (2001) Gras liefert Energie für die Stadt Schaffhausen, retrieved from: http://www.inaro.de/Deutsch/ROHSTOFF/ENERGIE/Biogas/Grasenergie.htm.
KOMPOGAS 2005	KOMPOGAS (2005) The KOMPOGAS Process. Kompogas AG, Glattbrugg, Switzerland, retrieved from: www.kompogas.com.
KOMPOGAS 2005	KOMPOGAS (2005) Mechanical-Biological Waste Treatment based on the KOMPOGAS Process. Kompogas AG, Glattbrugg, Switzerland, retrieved from: www.kompogas.com.
Markert 1997	Markert H. (1997) Bilanzierungen zur gekoppelten stofflichen und energetischen Biomasse-Verwertung. In proceedings from: 1. Symposiums „Grüne Bioraffinerie Brandenburg“, Brandenburgisches Umweltforschungszentrum, Neuruppin, 8.-9.10.1997.
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. FAL Reckenholz, FAT Tänikon, Swiss Centre for Life Cycle Inventories, Duebendorf, CH, retrieved from: www.ecoinvent.ch.
Ronchetti et al. 2002	Ronchetti C., Bient P. and Pridal R. (2002) Ökobilanz Klärgasverstromung. Bundesamt für Energie.
Schleiss 1999	Schleiss K. (1999) Grüngutbewirtschaftung im Kanton Zürich aus betriebswirtschaftlicher und ökologischer Sicht. Dissertation ETH Nr. 13476. Eidgenössische Technische Hochschule Zürich., Zurich.
Schleiss & Edelmann 2000	Schleiss K. and Edelmann W. (2000) Stromproduktion aus der Feststoff-Vergärung. Bundesamt für Energie und Biogasforum Schweiz,ENET, Baar.
Schleiss 2004	Schleiss K. (2004) Kompostier- und Vergärungsanlagen im Kanton Zürich. Amt für Abfall, Wasser, Energie und Luft (AWEL), Zürich.
Scholwin 2006	Frank Scholwin, Jens Michel, Gerd Schröder und Martin Kalies (2006) Ökologische Analyse einer Biogasnutzung aus nachwachsenden Rohstoffen, Institut für Energetik und Umwelt gGmbH (IE), Leipzig, 2006
Spielmann et al. 2004	Spielmann M., Kägi T., Stadler P. and Tietje O. (2004) Life cycle inventories of transport services. Final report ecoinvent 2000 No. 14. UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories, Duebendorf, CH, retrieved from: www.ecoinvent.ch.
Vogt 2002	Vogt R., Knappe F., Giegrich J. and Detzel A. (2002) Ökobilanz Bioabfallverwertung. Untersuchungen zur Umweltverträglichkeit von Systemen zur Verwertung von bioligisch-organischen Abfällen. In: Initiativen zum Umweltschutz, Vol. 52. Erich Schmidt Verlag, Berlin.
Wartmann, Engeli 2002	Wartmann Otto und Hans Engeli in BfE Jahresbericht 2002, Bern
Wulf 2006	Sebastian Wulf, Peter Jäger, Helmut Döhler (2006) Balancing of greenhouse gas emissions and economic efficiency for biogas-production through anaerobic co-fermentation of slurry with organic waste. In: Agriculture, Ecosystems and Environment 112 (2006) p. 178–185
Zah 2007	Rainer Zah, Heinz Böni, Marcel Gauch, Roland Hischier, Martin Lehmann & Patrick Wäger (Empa): Ökobilanz von Energieprodukten: Ökologische Bewertung von Biotreibstoffen, Im Auftrag des Bundesamtes für Energie, des Bundesamtes für Umwelt und des Bundesamtes für Landwirtschaft, Mai 2007.
Ziegler 2004	Ziegler C. (2004) Zürcher Kompost aus Sicht der Abnehmer. Diplomarbeit, Zürich.

13 Use and Upgrading of Biogas

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Review: Niels Jungbluth, ESU-services Ltd., Uster
Last changes: 2005

13.1 Introduction

In this chapter life cycle inventories of the further processing and use of biogas are presented:

- Biogas Production Mix
- Upgrading of biogas to natural gas quality
- Use of biogas as a fuel for co-generation in biowaste and sewage sludge fermentation plants
- Use of biogas as a fuel for co-generation in agricultural fermentation plants

Reserves, resources and use of product are presented in the previous chapter.

13.2 Characterisation of Energy Carrier

In Tab. 13.1 the properties of the biogas production mix and the produced methane from biogas are summarised.

Tab. 13.1 Summary of main properties of Swiss biogas production mix and produced methane

		Biogas Mix	Methane 96%
Methane	Vol. %	63.34	96.00
Carbon Dioxide	Vol. %	33.47	2.00
Methane	Kg/Nm^3	0.45244	0.68571
Carbon Dioxide	Kg/Nm^3	0.65713	0.03926
Total Carbon Content	Kg/Nm^3	0.51855	0.52499
Nitrogen	Vol. %	3.17	1.00
Density	Kg/Nm^3	1.15	0.75
Lower Heating Value	MJ/Nm^3	22.73	34.45

13.3 Life Cycle Inventories of Biogas Production Mix

Currently, biogas from biowaste, sewage sludge and liquid manure is available for further usages. Biogas from liquid manure is usually directly used on agricultural sites in co-generation plants equipped with ignition gas engines.

Biogas from biowaste and sewage sludge may be further upgraded to natural gas qualities or directly used in co-generation plants equipped with gas engines. In this project, a production mix is employed, representing the current production share of biogas from sewage sludge and biowaste in Switzerland. The shares of each digestion process are derived from figures presented in Tab. 12.1 (chapter biogas). Assuming that the production volume of biogas derived from sewage sludge co-fermentation merely accounts for 10% of the total production volume; the figure for biogas from sewage sludge as presented in Tab. 12.1 has been adjusted. As a consequence, biogas generated from sewage sludge dominates the production mix.

Tab. 13.2 Unit process raw data of the Swiss biogas production mix

	Name	Location	InfrastructureProcess	Unit	biogas, production mix, at storage	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	biogas, production mix, at storage	CH	0	Nm3	1.00000E+00			
Input	biogas, from agricultural co-digestion, at storage	CH	0	Nm3	0.00000E+00	1	1.05	
	biogas, from agricultural digestion, at storage	CH	0	Nm3	0.00000E+00	1	1.05	
	biogas, from grass, digestion, at storage	CH	0	Nm3	0.00000E+00	1	1.05	
	biogas, from sewage sludge, at storage	CH	0	Nm3	9.14450E-01	1	1.09	(2,3,1,1,1,1); national statistics and own assumptions
	biogas, from whey, digestion, at storage	CH	0	Nm3	0.00000E+00	1	1.05	
	biogas, from biowaste, at storage	CH	0	Nm3	8.55497E-02	1	1.05	(1,1,1,1,1,1); national statistics and own assumptions

13.4 Life Cycle Inventories of Biogas Purification

13.4.1 System Characterisation

Biogas purification (also referred to as biogas upgrading) aims to produce a gas of natural gas quality and feed it into the gas network or as a car fuel. Compared to natural gas, raw biogas is a heavy gas and the presence of incombustible CO_2 and water vapour reducing its calorific value and making it uneconomical to compress and transport over longer distances.

It is essential to remove

- CO_2 to shift the heating value of the gas.
- H_2S and water to tackle the corrosive quality of H_2S in water.

A comprehensive investigations on various technologies is available from Kapdi et al. (2005). The classical procedures are gas scrubbing, adsorption and CO_2 liquefaction. In recent years also wet and dry membrane separation processes have become available.

The data presented in this study refer to a modern biogas upgrading plant using a pressure swing adsorption technology (PSA) as illustrated in Fig. 13.1. This type of technology has recently been installed at the Water Treatment Plant Buholz in Switzerland.

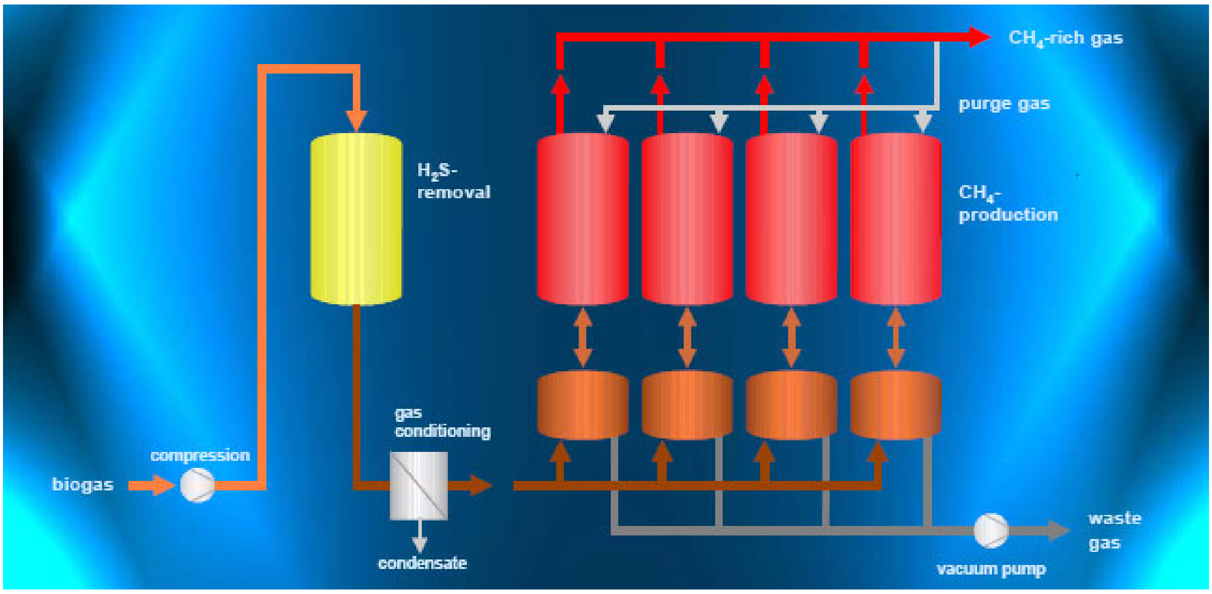

Fig. 13.1 Process scheme of a biogas upgrading plant using pressure swing adsorption (PSA) (RÜTGERS 2004)

The main steps of the PSA adsorption are:

1. Raw gas compression
2. H_2S-removal
3. Biogas conditioning
4. Methane production

In Fig. 13.2 the technical characteristics for are typical plant RÜTGERS (2004) are presented.

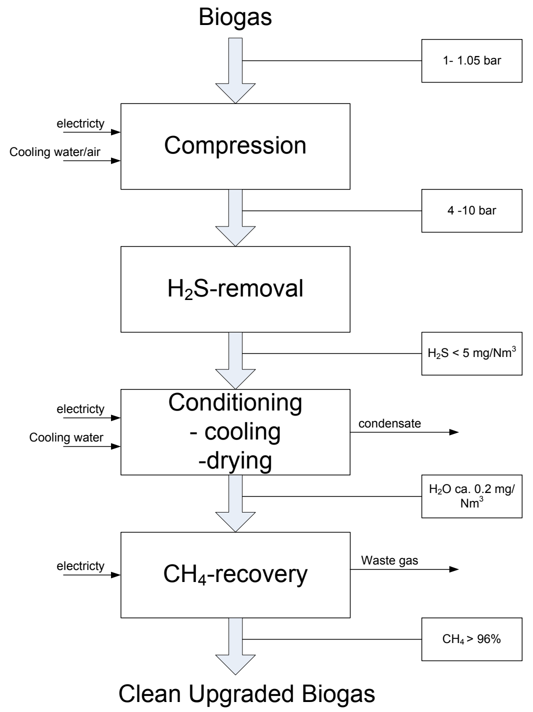

Fig. 13.2 Process flow chart of a biogas upgrading plant using pressure swing adsorption (PSA) (modified from (RÜTGERS 2004))

The raw biogas is first compressed and lead in the H_2S removal reactor. The H_2S removal is based on the principle of cracking the H_2S-molecule on an activated carbon surface at temperatures of 60-90 °C.

$2H_2S + O_2 \rightarrow 2H_2O + \frac{1}{4} S_8$

The sulphur is subsequently adsorbed on the surface of the activated carbon. The resulting H_2S content in the biogas is 5 mg/Nm^3 and lower. The life time for the removal adsorbent is about one year. However, no figures of the amount of adsorbent are available and thus it is not considered in this study. In the subsequent conditioning system the biogas temperature is reduce to app. 20- 30 °C and a dew point of app. 3-5 °C is obtained by means of cold drying. The drying serves as protection against corrosion of following parts.

The almost H_2S-free dry biogas is then lead into a four-bed-pressure swing-adsorption (PSA) plant to purify the methane. Every adsorber of the plant is operated in a four-step-cycle of adsorption, depressurisation, regeneration and depressurisation. According to the manufacturer, the absorber is totally regenerated by evacuation and thus there is no need for an exchange of adsorber material. Moreover, the manufacturer claims that there is no need for:

- an additional process water system,
- a waste water treatment (information about the quantity and treatment of cooling water is not available)

13.4.2 Infrastructure

For infrastructure facilities no data was readily available. Consequently, infrastructure expenditures are accounted for employing the generic module facilities chemical production.

13.4.3 Properties of the Upgraded Biogas (Product Gas)

In Tab. 13.3 the technical characteristics and the properties of the product gas (methane 96%) are presented. The product gas leaves the process with a pressure of 5 bar.

Tab. 13.3 Properties of product gas

Composition of Upgraded Biogas		Rütgers general 1)	Rütgers general 1)	Rütgers WTP Luzern 2)	Rütgers WTP Luzern 2)	This project 3)
CH_4 (v_{CH4})		≥ 96%	96.00%	≥ 94%	96.00%	96.00%
CO_2 (v_{CO2})		≤ 2%	2.00%	≤ 3%	2.00%	2.00%
N_2 (v_{N2})		≤ 2%	1.00%	≤ 3%	1.00%	1.00%
H_2S (v_{H2S})		≤ 5 mg/Nm3	0.0003%	≤ 5 mg/Nm3	0.0010%	0.0010%
O_2 (vO_2)		≤ 2%	1.00%	≤ 3%	1.00%	0.9997%
Density	kg/Nm^3		0.738		0.738	0.752
Lower Heating Value (LHV)	MJ/Nm^3					34.450
Upper Heating Value (UHV)	MJ/Nm3					38.146

1: RÜTGERS (2004) (first column the information available, second column the data used for the calculation of the value for this study)

2: Oral Communication with Mr. Ronchetti (SwissTS). The data is derived from an offer of the manufacturer Rütgers for the wastewater treatment plant in Buholz. (first column the information available, second column the data used for the calculation of the value for this study)

3. Density value is based on own calculations according to the biogas composition.

13.4.4 Fuel and Energy Input

Biogas consumption

In Tab. 13.4 data of the process efficiency – presenting the actual amount of biogas required for the generation of one cubic meter of product gas – from different sources is summarised.

Tab. 13.4 Process Efficiency

Technical Charcteristics	Unit	Rütgers general 1)	Rütgers WTP Luzern 2)	Erdgas Zuerich 3)	This project
Biogas input	Nm3/h	400	60	55	
Product gasoutput	Nm3/h	260	40.2	33	
Waste gas output	Nm3/h	140	19.8	22	
Biogas per product gas	Nm3 Biogas/Nm3 CH4	1.54	1.49	1.67	1.50

1: RÜTGERS 2004

2: Oral Communication with Mr. Ronchetti (SwissTS). The data is derived from an offer of the manufacturer Rütgers for the wastewater treatment plant in Buholz.

3: Oral communication with Erdgas Zürich.

In this study an average value of 1.50 $Nm^3_{Biogas}/ Nm^3_{Product\ Gas}$ is employed.

Electricity consumption

Figures for the electricity consumption for the total PSA biogas upgrading plant are available from RÜTGERS (2004).

It should be noted that these figures are not based on measurements of a particular plant in operation, but merely represent information available from the manufacturer of such plants (RÜTGERS 2004). For the plant operated by "Erdgas Zürich" no information about the underlying technology was available. Thus, in this study we employ the data available from RÜTGERS (2004), and slightly increase the value, to account for the fact that this data is probably a best case assumption of the manufacturer.

Tab. 13.5 Electricity consumption for biogas purification

	Unit	Rütgers general 1)	Erdgas Zuerich 2)	This study
Total Electricty Consumption	kW	87	33	
Product Gas	Nm^3/h	260	33	
total Energy Consumption	kWh/m^3 Product Gas	0.33	1.00	0.5

1: RÜTGERS 2004

2: Oral communication with Erdgas Zürich.

13.4.5 Emissions to Air

Emissions to air are based on the composition of the waste gas as presented in Tab. 13.6. For biogenic CO_2-emissions, the figures are adjusted in a way that the Carbon input-output balance is fulfilled.

Tab. 13.6 Properties of waste gas

Properties Waste Gas (p= 1bar a; T= 50°C)	Unit	Rütgers general 1)	Rütgers WTP Luzern 2)	This project 3)
CH4	%	7.00	5.00	6
CO2	%	89.00	92.30	90.65
N2/O2	%	4.00	2.70	3.35
Trace Elements (H2S)	%	4.46E-04	4.46E-04	4.46E-04

1: RÜTGERS 2004

2: Oral Communication with Mr. Ronchetti (SwissTS). The data is derived from an offer of the manufacturer Rütgers for the wastewater treatment plant in Buholz.

3: The value for CO_2-emissions is only of theoretical nature, since CO2-emissions are adjusted in a way that the Carbon input-output is fulfilled.

In this study we assume that all components in the waste gas are not further used. Consequently, the total quantity of the waste gas is accounted for as emission to air. The resulting figures are presented in Tab. 13.7.

Tab. 13.7 Emissions to air from waste gas

Gas	Unit	Carbotech general 1)	Carbotech WTP Luzern 2)	This project 3)
Ratio Waste Gas / Product Gas	$Nm^3_{waste}/Nm^3_{product}$	0.54	0.49	0.52
CO2-emissions	kg $CO_2/Nm^3_{product}$	9.41E-01	8.93E-01	8.66E-01
CH4-emissions	kg $CH_4/Nm^3_{product}$	2.69E-02	1.76E-02	2.23E-02
H2S-emissions	kg $H_2S/Nm^3_{product}$	3.64E-06	3.33E-06	3.49E-06

1: RÜTGERS (2004)

2: Oral Communication with Mr. Ronchetti (SwissTS). The data is derived from an offer of the manufacturer Rütgers for the wastewater treatment plant in Buholz.

3: The value for CO_2-emissions represents the calculated value which has been adjusted in a way that the Carbon input-output is fulfilled.

Sulphur obtained in the H_2S removal reactor is accounted for as sulphur dioxide emission, assuming that the total amount is oxidised afterwards. Based on the difference of H_2S-input and the amount of H_2S in the product and waste gas, we derived a sulphur dioxide emission of 8.27E-04 kg/Nm^3 product gas.

13.4.6 Life Cycle Inventory Input Data

In Tab. 13.8 the input data of the biogas upgrading process is presented.

Tab. 13.8 Unit process raw data of biogas purification and methane enrichment

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol-%, from biogas, at purification	UncertaintyType	StandardDeviation95%	GeneralComment	biogenic carbon content	biogenic carbon balance
	Location				CH					
	InfrastructureProcess				0					
	Unit				Nm3				%	Nm3
product	methane, 96 vol-%, from biogas, at purification	CH	0	Nm3	1.00E+0				52.5%	0.5250
technosphere	biogas, production mix, at storage	CH	0	Nm3	1.500000	1	1.16	(3,4,1,1,1,3); literature studies and own calculations. Basic uncertainty has been adjusted based on variations of literature data.	51.9%	0.7778
	electricity, medium voltage, at grid	CH	0	kWh	0.500000	1	2.03	(3,4,1,1,1,3); literature studies and own calculations (basic uncertainty is increased to 2.,0, in contrast to standard values)		
	facilities, chemical production	RER	1	kg	4.0E-11	1	3.09	(4,5,n.a,n.a,n.a,n.a); rough estimation		
emissions to air	Carbon dioxide, biogenic	-	-	kg	0.865856	1	1.21	(1,1,1,3,1,3); literature studies and own calculations (basic uncertainty is increased, in contrast to standard values)	27.3%	0.2361
	Methane, biogenic	-	-	kg	0.022257	1	1.17	(2,1,1,3,1,3); literature studies and own calculations (basic uncertainty is increased, in contrast to standard values)	75.0%	0.0167
	Hydrogen sulfide	-	-	kg	3.49E-06	1	1.13	(2,1,1,3,1,3); literature studies and own calculations (basic uncertainty is increased, in contrast to standard values)	0.0%	0.0000
	Sulfur dioxide	-	-	kg	8.27E-04	1	1.13	(2,1,1,3,1,3); literature studies and own calculations (basic uncertainty is increased, in contrast to standard values)	0.0%	0.0000
	Heat, waste	-	-	MJ	1.8	1	2.03	(3,4,1,1,1,3); literature studies and own calculations (basic uncertainty is increased to 2.,0, in contrast to standard values)	0.0%	0.0000
carbon ballance	Carbon input			kg						0.7778
	Carbon output			kg						0.2528
	Carbon in product gas			kg						0.5250
	Total Carbon out (Waste & Product Gas)			kg						0.7778
	balance			kg						0.0000

Data quality considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data available from literature studies. The inventory is not based on measurements of a particular plant in operation, but merely represents information available from the manufacturer of such plants.

13.5 Life Cycle Inventories of Gas Engine Co-generation

13.5.1 System Characterisation

A comprehensive analysis of various types of gas engine co-generation units is presented in Heck (2003). If not explicitly stated, system boundaries and basic assumptions for the co-generation of biogas are taken from the latter study. In this study we distinguish two different types of co-generation units:

1. co-generation unit at fermentation plants for biowaste and raw sewage sludge (approximately 160 kWh_{el}).

2. co-generation used at agricultural manure fermentation plants (ignition gas engine with additional diesel; approximately 50-70 kWh_{el}).

Allocation

For co-generation, in- and outputs have to be allocated in two products:

- Electricity and
- Heat

For the allocation various concepts may be employed and have been discussed in Heck (2003). In this project the exergy content is employed as allocation scheme. In such a case, the high quality energy electricity is assigned a higher environmental burden than heat. The allocation factors f_k can be determined as follows:

$$f_k = \frac{w_k \eta_k}{\sum_l w_l \eta_l}$$

$$\begin{aligned}&with\\ &w_k: exergy\ value\ of\ co-product\ k\\ &\eta_k: rate\ of\ capacity\ utilisation\end{aligned}$$

The allocation factors are consequently normalised:

$$\sum f_k = 1$$

13.5.2 Life Cycle Inventories for Biogas Co-generation with an Engine Power of 160 kWh_{el}

Technical Characteristics

In line with Schleiss (2000) we assume a co-generation unit with an engine power of 160 kWh_{el} for electricity generation at biowaste fermentation plants. In Heck (2003) two different alternatives are available. In this study we refer to the variant “typical”, representing a representative gas engine co-generation unit for the year of 2000 equipped with a “lambda 1-engine” with a catalytic converter. A detailed description of the technology is given in Heck (2003). The actual gains and losses of electricity and heat are summarised in Tab. 13.9. It should be noted, that alternatively also a lean mix engine without a catalyst may be used.

Tab. 13.9 Gains and losses of electricity and heat for a co-generation unit of 160 kWh_{el}

heat generation	MJ/Mj_{in}	0.55
eletricity generation	MJ/Mj_{in}	0.32
total energy output	MJ/Mj_{in}	0.87
heat losses	MJ/Mj_{in}	0.13
ratio upper heating value/ lower heating value		1.11
heat waste	MJ/Mj_{in}	0.75

Infrastructure

In Heck (2003) an in-depth investigation of infrastructure expenditures for co-generation units is presented. The data is further summarised in three datasets, representing common infrastructure expenditures as well as heat and electricity specific infrastructures.

Biogas input

According to the characteristics and the mix of biogas from biowaste and sewage sludge, we employ a lower heating value of 22.73 MJ/Nm^3; i.e. 0.044 Nm^3/MJ$_{in}$ of biogas are required.

Operational supplements

In line with Heck (2003) we assume a lubricate consumption of 0.03 g/MJ$_{in}$.

Emissions to air

CO_2-emisions are calculated based on the carbon content of the biogas mix. The value presented in Tab 13.1 is further corrected taken into account carbon emitted in form of CO and CH_4. Emission data of the latter pollutants as well as emission data of NO_x, N_2O and platinum (catalyst use) are taken from Heck 2003. SO_2-emissions are derived from the sulphur content of the biogas. Assuming a sulphur content of 300 mg/m^3 we obtain an SO_2-emission factor of 25 mg SO_2/MJ$_{In}$.

For a “lambda 1-engine” with a catalytic converter NO_x-emissions are accounted for with 15 mg/MJ$_{in}$. In case a lean-mix engine without a catalyst is used, emissions up to 400 mg/m^3 (exhaust gas volume) for biogenic fuels are in line with the current “Emissionsgrenzwerte für stationäre Verbrennungsmotoren nach der Schweizer Luftreinhalteverordnung” [36].

Tab. 13.10 CO_2-emissions and underlying assumptions

Carbon content in biogas	kg/Nm3	0.5186
Carbon content per heating value	kgC/MJ$_{biogas}$	0.0228
C in form of CO2	kg/MJ$_{biogas}$	0.0228
CO_2-emissions	kg/MJ$_{biogas}$	0.0835

Allocation

As stated above, the exergy content is employed as allocation parameter in this project. In Tab. 13.11 the resulting allocation factors and underlying assumptions are summarised.

Tab. 13.11 Allocation factors, exergy values and rate of capacity utilisation

	Electricity	Heat
Rate of capacity utilisation	0.32	0.55
Exergy value	1	0.17
Allocation factor	0.77	0.23

Life Cycle inventory Input data

In Tab. 13.12 the input data of the co-generation unit process is presented.

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[36] LRV (2000) Luftreinhalte-Verordnung vom 16. Dezember 1985 (LRV). (Stand am 28. März 2000). Schweizerischer Bundesrat, Bern, Online-Version unter: http://www.admin.ch/ch/d/sr/c814_318_142_1.html.

Tab. 13.12 Unit process raw data of biogas gas, burned in cogen with gas engine

	Name	Location	InfrastructureProcess	Unit	biogas gas, burned in cogen with gas engine	UncertaintyType	StandardDeviation95%	GeneralComment	heat, at cogen with biogas engine, allocation exergy	electricity, at cogen with biogas engine, allocation exergy
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated products	heat, at cogen with biogas engine, allocation exergy	CH	0	MJ	5.50000E-01				100	0
	electricity, at cogen with biogas engine, allocation exergy	CH	0	kWh	8.88889E-02				0	100
technosphere	cogen unit 160kWe, common components for heat+electricity	RER	1	unit	5.00000E-09	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	22.6	77.4
	cogen unit 160kWe, components for electricity only	RER	1	unit	5.00000E-09	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	-	100.0
	cogen unit 160kWe, components for heat only	RER	1	unit	5.00000E-09	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	100.0	-
	biogas, production mix, at storage	CH	0	Nm3	4.39902E-02	1	1.26	(1,4,2,1,3,4); own calculations based onlower heating value of biogas	22.6	77.4
	lubricating oil, at plant	RER	0	kg	3.00000E-05	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximation	22.6	77.4
waste	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	3.00000E-05	1	1.26	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	Heat, waste	-	-	MJ	7.53667E-01	1	1.26	(1,4,2,1,3,4); own calculations	85.2	14.8
emission air, low population density	Nitrogen oxides	-	-	kg	1.50000E-05	1	2.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	Carbon monoxide, biogenic	-	-	kg	4.80000E-05	1	2.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	Carbon dioxide, biogenic	-	-	kg	8.35024E-02	1	1.26	(1,4,2,1,3,4); own calculations based on carbon content in biogas	22.6	77.4
	Methane, biogenic	-	-	kg	2.30000E-05	1	3.07	(1,4,1,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.00000E-06	1	3.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	Dinitrogen monoxide	-	-	kg	2.50000E-06	1	3.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4
	Sulfur dioxide	-	-	kg	2.10043E-05	1	1.26	(1,4,2,1,3,4); own calculations based on sulphur content in biogas	22.6	77.4
	Platinum	-	-	kg	7.00000E-12	1	5.08	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	22.6	77.4

Data quality considerations

In this study we assume that the uncertainty ranges are in the same magnitude as for a comparable application of natural gas. Consequently we employ the same uncertainty ranges as presented in Heck (2003).

13.5.3 Life Cycle Inventories for Biogas Co-Generation on Agricultural Sites

Technical characteristics

According to Edelmann (2001) for the co-generation on agricultural plants, ignition gas engines using a supplement of diesel fuels are widely used. Typically, agricultural co-generation units are characterised by an energy power of 50-70 kWh_{el} with a share of 10 kWh_{el} generated by diesel fuels.

In this study, we assume a "lean burn engine" without a catalytic converter, resulting in high specific NO_x-emissions. Data of a similar gas engine with an energy power of 50 kWh_{el} is available from Heck (2003). Heck (2003), stated a degree of efficiency for electricity of 0.3. Edelmann 2001, in contrast assumes a slightly higher degree of efficiency (0.33) as a consequence of the additional use of diesel as a fuel. The resulting gains and losses of electricity and heat are summarised in Tab. 13.13.

Tab. 13.13 Gains and losses of electricity and heat for a co-generation unit with gas ignition engine

heat generation	MJ/Mj_{in}	0.54
eletricity generation	MJ/Mj_{in}	0.33
total energy output	MJ/Mj_{in}	0.87
lost heat	MJ/Mj_{in}	0.13
ratio upper heating value/ lower heating value		1.11
heat waste	MJ/Mj_{in}	0.74

Infrastructure

In Heck (2003) an in depth investigation of infrastructure expenditures for co-generation units is presented. The data is further summarised in three datasets, representing common infrastructure expenditures as well as heat and electricity specific infrastructures.

Biogas and diesel consumption

According to the characteristics of biogas from manure, as outlined in the previous chapter, we employ a lower heating value of 24.04 MJ/Nm^3, hence, 0.04 Nm^3/MJ_{in} of biogas are required. In addition, in line with Edelmann (2001) we assume a diesel consumption of 0.05 kg/kg_{biogas}.

Operational supplements

In line with Heck (2003) we assume a lubricate consumption of 0.03 g/MJ_{in}.

Emissions to air

CO_2-emisions are calculated based on the carbon content in the biogas. The value presented in Tab. 13.14 is further corrected taken into account carbon emitted in form of CO and CH_4.

Tab. 13.14 CO_2-emissions and underlying assumptions

Carbon content in biogas	kg/Nm3	0.5306
Carbon content per heating value	kgC/MJ_{biogas}	0.0221
C in form of CO2	kg/MJ_{biogas}	0.0219
CO_2-emissions	kg/MJ_{biogas}	0.0805

Emission data of airborne emissions are available from various sources. CH_4, CO and NMHC are available from Edelmann (2001). In addition, data of particle emissions and N_2O are presented in Heck (2003). SO_2-emissions are derived from the sulphur content of the biogas. Assuming sulphur content of 300 mg/Nm^3, we obtain a SO_2-emission of 25 mg SO_2/MJ_{In}. The value for NO_x-emissions represents the upper Swiss limit (LRV) for co-generation plants using biogas as feedstock (400 mg/Nm^3, 5% 0_2). In Tab. 13.15 emissions data from various sources and the data employed in this project are summarised.

Tab. 13.15 Airborne emissions of agricultural co-generation.

	Unit	emissions biogas (no Catalyst) 1)	emissions share diesel 1)	160 kW_{el} (incl. Catalyst) 2)	50 kW_{el} (no catalyst) 2)	emissions biogas this project 3)	total injection gas engine this project
diesel input	kg/ MJ_{biogas}		2.33E-03				2.33E-03
carbon dioxide biogenic	kg/ MJ_{biogas}	8.13E-02				8.05E-02	8.05E-02
carbon dioxide fossil	kg/ MJ_{biogas}		8.38E-03	5.60E-02	5.60E-02		8.38E-03
carbon monoxide biogenic	kg/ MJ_{biogas}	1.36E-04				1.60E-04	1.60E-04
carbon monoxide fossil	kg/ MJ_{biogas}		1.26E-05	2.88E-04	1.60E-04		1.26E-05
nitrogen oxide 5)	kg/ MJ_{biogas}	5.45E-05	5.76E-06	1.50E-05	7.00E-05	7.00E-05	1.28E-04
sulphur dioxide	kg/ MJ_{biogas}	3.35E-05	1.20E-05	5.50E-07	5.50E-07	2.50E-05	3.70E-05
methane biogenic	kg/ MJ_{biogas}	2.78E-06				8.00E-05	8.00E-05
methane fossil	kg/ MJ_{biogas}		2.62E-07	2.30E-05	8.00E-05		2.62E-07
NMVOC	kg/ MJ_{biogas}	2.78E-06	2.62E-07	2.00E-06	1.00E-05	1.00E-05	1.03E-05
dinitrogen monoxide	kg/ MJ_{biogas}			2.50E-06	5.00E-06	5.00E-06	5.00E-06
particulates 4)	kg/ MJ_{biogas}	0		1.50E-07	1.50E-07	1.50E-07	1.25E-06
platinum	kg/ MJ_{biogas}			7.00E-12		0.00E+00	0.00E+00

1: data available from Edelmann 2001

2: data available from Heck 2003

3: data used in this study mainly based on Heck 2003. Values of CO_2 and SO_2 are based on own calculations.

4: The value for particle emissions is derived from the current threshold of the German TA-Luft and experiences from practise

5: The value for NO_x-emissions (in the last column) represents the upper Swiss limit (LRV) for co-generation plants using biogas as feedstock.

Allocation

As stated above, the exergy content is employed as allocation parameter in this project. In Tab. 13.16 the resulting allocation factors and underlying assumptions are summarised.

Tab. 13.16 Allocation factors, exergy values and rate of capacity utilisation

	Electricity	Heat
Rate of capacity utilisation	0.33	0.54
Exergy value	1	0.17
Allocation factor	0.78	0.22

Life cycle inventory input data

In Tab. 13.17 the input data of the co-generation unit process are presented.

Tab. 13.17 Unit process raw data of co-generation at agricultural manure fermentation plants

	Name	Location	InfrastructureProcess	Unit	biogas, burned in cogen with ignition gas engine	UncertaintyType	StandardDeviation95%	GeneralComment	heat, at cogen with ignition biogas engine, allocation	electricity, at cogen with ignition biogas engine, allocation
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, at cogen with ignition biogas engine, allocation exergy	CH	0	MJ	5.93838E-01				100	0
products	electricity, at cogen with ignition biogas engine, allocation exergy	CH	0	kWh	1.00806E-01				0	100
technosphere	cogen unit 50kWe, common components for heat+electricity	RER	1	unit	1.67000E-08	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	21.8	78.2
	cogen unit 50kWe, components for electricity only	RER	1	unit	1.67000E-08	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	-	100.0
	cogen unit 50kWe, components for heat only	RER	1	unit	1.67000E-08	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	100.0	-
	biogas, from agricultural digestion, at storage	CH	0	Nm3	4.15973E-02	1	1.26	(1,4,2,1,3,4); own calculations based on lower heating value of biogas	21.8	78.2
	diesel, at regional storage	CH	0	kg	2.32945E-03	1	1.26	(1,4,2,1,3,4); literature studies	21.8	78.2
	lubricating oil, at plant	RER	0	kg	3.00000E-05	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximation	21.8	78.2
waste	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	3.00000E-05	1	1.26	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximation	21.8	78.2
	Heat, waste	-	-	MJ	8.32417E-01	1	1.26	(1,4,2,1,3,4); own calculations	83.6	16.4
	Nitrogen oxides	-	-	kg	1.28000E-04	1	2.07	(1,4,2,1,3,4); LRV emission limit biogas	21.8	78.2
	Carbon monoxide, biogenic	-	-	kg	1.60000E-04	1	2.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as a first approximination	21.8	78.2
	Carbon monoxide, fossil	-	-	kg	1.25731E-05	1	2.07	(1,4,2,1,3,4); literature data for emssions due to to diesel ignition	21.8	78.2
	Carbon dioxide, biogenic	-	-	kg	8.04510E-02	1	1.26	(1,4,2,1,3,4); value for cogeneration of natural gas used as a first approximination	21.8	78.2
	Carbon dioxide, fossil	-	-	kg	8.38206E-03	1	1.26	(1,4,2,1,3,4); literature data for emssions due to to diesel ignition	21.8	78.2
	Methane, biogenic	-	-	kg	8.00000E-05	1	3.07	(1,4,1,1,3,4); value for cogeneration of natural gas used as a first approximination	21.8	78.2
	Methane, fossil	-	-	kg	2.61939E-07	1	3.07	(1,4,1,1,3,4); literature data for emssions due to to diesel ignition	21.8	78.2
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.02619E-05	1	3.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximination and literature value for emssions due to to diesel ignition	21.8	78.2
	Dinitrogen monoxide	-	-	kg	5.00000E-06	1	3.07	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximination	21.8	78.2
	Particulates, < 2.5 um	-	-	kg	1.24792E-06	1	2.07	(1,4,2,1,3,4); value is derived from the threshold of the German TA-Luft and experiences from practise. Basic uncertainties are adjusted	21.8	78.2
	Sulfur dioxide	-	-	kg	3.70076E-05	1	1.26	(1,4,2,1,3,4); value for cogeneration of natural gas used as approximination and literature value for emssion due to to diesel ignition	21.8	78.2

Data quality considerations

In this study we assume that the uncertainty ranges are in the same magnitude as for a comparable application of natural gas. Consequently, we employ the same uncertainty ranges as presented in Heck 2003.

13.5.4 Production of electricity and heat from agricultural biogas for the year 2006

The process for cogeneration of agricultural biogas is based on the general processes for biogas cogeneration, see chapter 13.5.2 and 13.5.3. The following adoption has been done:

- The input has been changed to the agricultural biogas production in the year 2006
- The allocation has been adopted
- The CO_2 emission has been recalculated to get a correct carbon balance

Biogas and co-generation plant used

There are two types of agricultural biogas production evaluated in this project:

- Biogas plant with a covered stock and methane recovery
- Biogas plant without a covered stock, leading to higher methane emissions

Two types of co-generation plants have been evaluated:

- Biogas engine
- Biogas ignition engine

This leads to following four different possibilities:

- biogas, agriculture covered, in cogen with biogas engine
- biogas, agriculture covered, in cogen with ignition biogas engine
- biogas, agriculture, in cogen with biogas engine
- biogas, burned in cogen with ignition gas engine

The biogas mix has been evaluated considering the share of the different electricity production in the year 2006. This data are based on the evaluation of 20 biogas plants, see Tab. 13.18, and the fact that older and smaller biogas plants are equipped with an ignition engine.

Tab. 13.18 Electricity production from biogas in Switzerland in the year 2006, based on data from naturmade and Konrad Schleiss

	covered & trail hose	not covered or no trail hose		covered & trail hose	not covered or no trail hose
ignition	2'036	7'080	kWh	8.15%	28.32%
gas engine	13'760	2'124	kWh	55.04%	8.50%

Allocation

For co-generation, in- and outputs have to be allocated in two products:

- Electricity and
- Heat

For the allocation various concepts may be employed see also chapter 13.5. In this project the exergy content is employed as allocation scheme. In such a case, the high quality energy electricity is assigned a higher environmental burden than heat. The allocation factors f_k can be determined as follows:

$$f_k = \frac{w_k \eta_k}{\sum_l w_l \eta_l}$$

with

w_k : *exergy value of co – product k*

η_k : *rate of capacity utilisation*

The allocation factors are consequently normalised:

$$\sum f_k = 1$$

The following table shows the used energy and the following allocation factors. The data are based on the evaluation of 20 bioenergy plants, see also table Tab. 13.19.

Tab. 13.19 Energy use and allocation factors for the agricultural biogas plants in Switzerland in the year 2006

Used heat per Nm^3 of biogas for			electricity	waste heat	
the biogas process	external use	sum			
4.96	2.17	7.13		9.39	MJ
1.38	0.60	1.98	2.09	2.61	kWh
		30%	31%	39%	

	Electricity	Used Heat
Rate of capacity utilisation	31%	30%
Exergy value	1	0.17
Allocation factor	86.14%	13.86%

Carbon balance

To get a correct carbon balance the CO_2 emissions have been recalculated from the input (biogas) and the other carbon containing emissions like CO and NMVOC.

Tab. 13.20 Unit process raw data of the co-generation with a biogas engine

	Name	Location	InfrastructureProcess	Unit	biogas, agricultur covered, in cogen with biogas engine	UncertaintyType	StandardDeviation95 %	GeneralComment	heat, at cogen with biogas engine, agricultural covered, allocation exergy	electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	Biogenic carbon content	biogenic carbon balance
	Location				CH				CH	CH		
	InfrastructureProcess				0				0	0		
	Unit				MJ				MJ	kWh		
allocated	heat, at cogen with biogas engine, agricultural covered, allocation exergy	CH	0	MJ	0.55				100	0		
products	electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	CH	0	kWh	8.89E-2				0	100		
technosphere	cogen unit 160kWe, common components for heat+electricity	RER	1	unit	5.00E-9	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	13.9	86.1		
	cogen unit 160kWe, components for electricity only	RER	1	unit	5.00E-9	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	-	100.0		
	cogen unit 160kWe, components for heat only	RER	1	unit	5.00E-9	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	100.0	-		
	biogas, mix, at agricultural co-fermentation, covered	CH	0	Nm3	4.16E-2	1	1.22	(1,3,1,1,3,3); Needed heat is produced by the cogeneration	13.9	86.1	53.06%	0.0221
	lubricating oil, at plant	RER	0	kg	3.00E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	3.00E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
emission air, low population density	Heat, waste	-	-	MJ	6.20E-1	1	1.26	(1,4,2,1,3,4); own calculation	54.6	45.4		
	Nitrogen oxides	-	-	kg	1.50E-5	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	Carbon monoxide, biogenic	-	-	kg	4.80E-5	1	5.08	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination and entered as biogenic CO	13.9	86.1	42.9%	0.0000
	Carbon dioxide, biogenic	-	-	kg	8.08E-2	1	1.26	(1,4,2,1,3,4); calculated from C Input	13.9	86.1	27.27%	0.0220
	Methane, biogenic	-	-	kg	2.30E-5	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination and entered as biogenic methane	13.9	86.1	0.75	0.0000
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.00E-6	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1	80.00%	0.0000
	Dinitrogen monoxide	-	-	kg	2.50E-6	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	Sulfur dioxide	-	-	kg	2.10E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	Platinum	-	-	kg	7.00E-12	1	5.08	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
Carbon balance	Input: Carbon from bio sources											0.02207
	Output: Carbon from bio sources											0.02207

Tab. 13.21 Meta information of the co-generation with a biogas engine

ReferenceFunction	401		biogas, agricultur covered, in cogen with biogas engine
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	MJ
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Use of biogas in a cogeneration unit. Included are emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure expenditures.
	404	Amount	1
	490	LocalName	Biogas, Landwirtschaft abgedeckt, in BHKW mit Gasmotor
	491	Synonyms	
	492	GeneralComment	The multioutput process "biogas, agricultur covered, in cogen with biogas engine" delivers the co-products: heat "heat, at cogen with biogas engine, agricultural covered, allocation exergy" and electricity "electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy". The allocation is based on the exergy values of heat and electricity. The exergy value of electricity is 1, and the exergy value of heat is 0.17. The degrees of efficiency are as follows: electricity: 33% and heat: 67%, but in these plants only half of the heat is used or sold (32%).
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1993
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	Conditions of cogeneration in Switzerland.
Technology	692	Text	Lambda 1-engine" with a catalytic converter
Representativene	722	Percent	100
	724	ProductionVolume	15.1 GWh electricity in this typ of plant
	725	SamplingProcedure	field data
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	68
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Tab. 13.22 Unit process raw data of the co-generation with an ignition biogas engine

	Name	Location	InfrastructureProcess	Unit	biogas, agricultur covered, in cogen with ignition biogas engine	UncertaintyType	StandardDeviation95 %	GeneralComment	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	Biogenic carbon content	biogenic carbon balance
	Location				CH				CH	CH		
	InfrastructureProcess				0				0	0		
	Unit				MJ				MJ	kWh		
allocated	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	CH	0	MJ	0.59				100	0		
products	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	CH	0	kWh	1.01E-1				0	100		
technosphere	cogen unit 50kWe, common components for heat+electricity	RER	1	unit	1.67E-8	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	13.9	86.1		
	cogen unit 50kWe, components for electricity only	RER	1	unit	1.67E-8	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	-	100.0		
	cogen unit 50kWe, components for heat only	RER	1	unit	1.67E-8	1	3.07	(1,4,2,1,3,4); ecoinvent V1.1. cogeneration of natural gas.	100.0	-		
	biogas, mix, at agricultural co-fermentation, covered	CH	0	Nm3	4.16E-2	1	1.22	(1,3,1,1,3,3); own calculation based on lower heating value of biogas	13.9	86.1	53.06%	0.02207
	diesel, at regional storage	CH	0	kg	2.33E-3	1	1.22	(1,3,1,1,3,3); literature studies	13.9	86.1		
	lubricating oil, at plant	RER	0	kg	3.00E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	3.00E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
emission air, low population density	Heat, waste	-	-	MJ	6.83E-1	1	1.26	(1,4,2,1,3,4); own calculation	54.6	45.4		
	Nitrogen oxides	-	-	kg	1.28E-4	1	1.59	(1,4,2,1,3,4); LRV limitation biogas	13.9	86.1		
	Carbon monoxide, biogenic	-	-	kg	1.60E-4	1	5.08	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination and entered as biogenic CO	13.9	86.1	42.9%	0.0001
	Carbon monoxide, fossil	-	-	kg	1.26E-5	1	5.08	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination for the diesel used	13.9	86.1		
	Carbon dioxide, biogenic	-	-	kg	8.04E-2	1	1.26	(1,4,2,1,3,4); own calculation	13.9	86.1	27.27%	0.0219
	Carbon dioxide, fossil	-	-	kg	8.38E-3	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination for the diesel used	13.9	86.1		
	Methane, biogenic	-	-	kg	8.00E-5	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination and entered as biogenic methane	13.9	86.1	0.75	0.0001
	Methane, fossil	-	-	kg	2.62E-7	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination for the diesel used	13.9	86.1		
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.03E-5	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1	80.00%	0.0000
	Dinitrogen monoxide	-	-	kg	5.00E-6	1	1.59	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	Particulates, < 2.5 um	-	-	kg	1.25E-6	1	3.07	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
	Sulfur dioxide	-	-	kg	3.70E-5	1	1.26	(1,4,2,1,3,4); value of cogeneration of natural gas used as approximination	13.9	86.1		
Carbon balance	Input: Carbon from bio sources											0.02207
	Output: Carbon from bio sources											0.02207

Tab. 13.23 Meta information of the co-generation with an ignition biogas engine

ReferenceFuncti on	401		biogas, agricultur covered, in cogen with ignition biogas engine
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	MJ
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Use of biogas in a cogeneration unit. In addition to biogas also diesel is used as a fuel (0.05 kg diesel per kg biogas). Included are emissions to air, biogas consumption, use and disposal of operational supplements. The calculated emissions include emissions due to the combustion of bio gas and diesel. Infrastructure expenditures are accounted for, too.
	404	Amount	1
	490	LocalName	Biogas, Landwirtschaft abgedeckt, in BHKW mit Zündstrahlmotor
	491	Synonyms	
	492	GeneralComment	The multioutput process "biogas, agricultur covered, in cogen with ignition biogas engine" delivers the co-products: heat "heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy" and electricity "electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy". The allocation is based on the exergy values of heat and electricity. The exergy value of electricity is 1, and the exergy value of heat is 0.17. The degrees of efficiency are as follows: electricity: 0.33 and heat: 0.67. The evaluation of 20 plants have shown that 32% of the energy input is used as heat, 35% of the produced heat can not be used or sold. The value for particle emissions is derived from the current threshold of the German TA-Luft and experiences from practise. The value for NOx-emissions represents the upper Swiss limit for co-generation plants using biogas as feedstock.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1993
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	Conditions of co-generation in Switzerland.
Technology	692	Text	50 kWhel lean burn engine
Representativene	722	Percent	100
	724	ProductionVolume	2.0 GWh electricity in this typ of plant
	725	SamplingProcedure	field data
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	68
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Tab. 13.24 Unit process raw data of the process: Heat, at cogen, biogas agricultural mix, allocation exergy

	Name	Location	Unit	heat, at cogen, biogas agricultural mix, allocation exergy	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			MJ			
product	heat, at cogen, biogas agricultural mix, allocation exergy	CH	MJ	1			
technosphere	heat, at cogen with biogas engine, agricultural covered, allocation exergy	CH	MJ	5.50E-1	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.
	heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	CH	MJ	8.15E-2	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants. In the year 2006 a large amount of fat and oil were used to produce biogas. According to the market situation this can change in the future
	heat, at cogen with biogas engine, agricultural, allocation exergy	CH	MJ	8.50E-2	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants. In the year 2006 a large amount of fat and oil were used to produce biogas. According to the market situation this can change in the future
	heat, at cogen with ignition biogas engine, allocation exergy	CH	MJ	2.83E-1	1	1.08	(2,2,2,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.

Tab. 13.25 Meta information of the process: Heat, at cogen, biogas agricultural mix, allocation exergy

ReferenceFunction	401	Name	heat, at cogen, biogas agricultural mix, allocation exergy
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	MJ
DataSetInformatic	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	This process is an assembling process for the different production of heat from biogas
	404	Amount	1
	490	LocalName	Nutzwärme, ab BHKW, Biogas Landwirtschaft Mix, Allokation Exergie
	491	Synonyms	
	492	GeneralComment	This process gives the mix of heat from biogas from agricultural plants in Switzerland in the year 2006
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2006-01-01
	602	EndDate	2006-12-31
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	For this process 20 plants in Switzerland producing about 50% of electricity from biogas have been evaluated.
Technology	692	Text	Mix of biogas engines and ignition gas engine
Representativene	722	Percent	50
	724	ProductionVolume	25 GWh electricity, 12 mio. m3 Biogas
	725	SamplingProcedure	The data are the average of 20 plants in Switzerland
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	68
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	Passed
	5619	OtherDetails	none

Tab. 13.26 Unit process raw data of the process: Electricity, at cogen, biogas agricultural mix, allocation exergy

	3702	3703	3706	3707	3708	3709	3792
	Name	Location	Unit	electricity, at cogen, biogas agricultural mix, allocation Exergy	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, at cogen, biogas agricultural mix, allocation Exergy	CH	kWh	1			
technosphere	electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	CH	kWh	5.50E-1	1	1.06	(1,2,1,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.
	electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	CH	kWh	8.15E-2	1	1.06	(1,2,1,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants. In the year 2006 a large amount of fat and oil were used to produce biogas. According to the market situation this can change in the future
	electricity, at cogen with biogas engine, agricultural, alloc. Exergy	CH	kWh	8.50E-2	1	1.06	(1,2,1,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.
	electricity, at cogen with ignition biogas engine, allocation exergy	CH	kWh	2.83E-1	1	1.06	(1,2,1,1,1,2); Data from 20 plants in Switzerland producing about 50% of the biogas in agricultural biogas plants.

Tab. 13.27 **Meta information of the process: Electricity, at cogen, biogas agricultural mix, allocation exergy**

ReferenceFunction	401	Name	electricity, at cogen, biogas agricultural mix, allocation Exergy
Geography	662	Location	CH
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	kWh
DataSetInformatic	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	68
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	This process connects the different productions for electricity from agricultural biogas plants.
	404	Amount	1
	490	LocalName	Strom, ab BHKW, Biogas Landwirtschaft Mix, Allokation Exergie
	491	Synonyms	
	492	GeneralComment	This process gives the mix of electricity production from biogas from agricultural plants in Switzerland in the year 2006
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2006-01-01
	602	EndDate	2006-12-31
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	For this process 20 plants in Switzerland producing about 50% of electricity from biogas have been evaluated.
Technology	692	Text	Mix of biogas engines and ignition gas engine
Representativene	722	Percent	50
	724	ProductionVolume	25 GWh electricity, 12 mio. m3 Biogas
	725	SamplingProcedure	The data are the average of 20 plants in Switzerland
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	75
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	
ProofReading	5616	Validator	41
	5615	Details	automatic validation in Excel
	5619	OtherDetails	none

13.6 Cumulative Results and Interpretation

13.6.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows showing by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

13.6.2 Cumulative Results of Biogas Production Mix and Upgraded Biogas

The below table shows the selected LCI results and the cumulative energy demand for the applied biogas-mix and biogas upgrading.

Tab. 13.28 Selected LCI results and the cumulative energy demand for modelled biogas-mix and biogas upgrading

		Name		biogas, production mix, at storage	methane, 96 vol-%, from biogas, at purification
		Location		CH	CH
		Unit	Unit	Nm3	Nm3
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	4.86E+00	8.01E+00
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.60E+00	5.41E+00
	cumulative energy demand	renewable energy resources, water	MJ-Eq	5.16E-01	1.74E+00
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	9.84E-03	3.17E-02
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.31E-02	3.88E-02
LCI results					
resource	Land occupation	total	m2a	5.5E-3	1.2E-2
air	Carbon dioxide, fossil	total	kg	2.8E-1	4.7E-1
air	NMVOC	total	kg	1.2E-4	2.0E-4
air	Nitrogen oxides	total	kg	2.2E-4	4.2E-4
air	Sulphur dioxide	total	kg	1.7E-4	9.2E-4
air	Particulates, < 2.5 um	total	kg	1.4E-5	3.0E-5
water	BOD	total	kg	7.9E-5	1.5E-4
soil	Cadmium	total	kg	2.4E-11	6.1E-11
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-2.0E+0
air	Carbon dioxide, land transformation	low population density	kg	5.5E-7	8.7E-7
air	Methane, biogenic	total	kg	1.0E-6	2.2E-2
air	Carbon monoxide, biogenic	total	kg	1.6E-6	4.4E-6

A comparison of the fossil airborne emission scores of the biogas production mix (raw biogas) and the upgraded biogas shows considerably higher scores for the latter. This result indicates the environmental relevance of the upgrading process. As far as the biogenic emissions are considered, the results reveal a considerably increase of methane emissions as a consequence of biogas upgrading. This has to be interpreted carefully, as these results are influenced by the worst-case assumption of no further use/treatment of the process waste gas.

13.6.3 Cumulative Results for Co-Generation Processes

The below table shows the selected LCI results and the cumulative energy demand for co-generation processes investigated in this project. For the electricity and heat at cogen with biogas engine or ignition engine mainly biogas from sewage sludge is used. The agricultural plants use biogas from digesting slurry, fat & oil or catering waste.

Tab. 13.29 Selected LCI results and the cumulative energy demand for electricity from co-generation with biogas

Name			Electricity, at cogen with biogas engine, agricultural covered, alloc. Exergy	Electricity, at cogen with biogas engine, agricultural, alloc. Exergy	Electricity, at cogen with biogas engine, allocation exergy	Electricity, at cogen with ignition biogas engine, agric. covered, alloc. exergy	Electricity, at cogen with ignition biogas engine, allocation exergy	Electricity, at cogen, biogas agricultural mix, allocation Exergy
location			CH	CH	CH	CH	CH	CH
Unit			kWh	kWh	kWh	kWh	kWh	kWh
Infrastructure			0	0	0	0	0	0
energy ressources								
non-renewable								
fossil		MJ Eq	7.2E-2	1.5E-1	5.4E-1	3.7E-1	3.9E-1	1.9E-1
nuclear		MJ Eq	5.2E-2	6.4E-2	1.9E-1	5.1E-2	6.0E-2	5.5E-2
renewable		MJ						
biomass		MJ Eq	1.9E-2	8.4E-4	1.6E-3	1.7E-2	9.0E-4	1.2E-2
wind, solar, geothermal		MJ Eq	2.8E-4	3.3E-4	7.2E-4	3.1E-4	3.5E-4	3.1E-4
water		MJ Eq	2.7E-4	5.1E-4	2.2E-4	2.3E-4	5.8E-4	3.8E-4
selected LCI results								
NMVOC	air	kg	1.1E-5	1.8E-5	1.9E-5	4.2E-5	4.3E-5	2.3E-5
CO2, fossil	air	kg	5.1E-3	1.1E-2	3.1E-2	2.7E-2	3.0E-2	1.4E-2
sulphur dioxide	air	kg	8.7E-5	9.8E-5	8.5E-5	1.2E-4	1.2E-4	1.0E-4
nitrogen oxides	air	kg	6.4E-5	1.2E-4	6.1E-5	3.4E-4	3.5E-4	1.7E-4
particulates >10 um	air	kg	3.9E-6	6.3E-6	4.7E-6	4.2E-6	7.0E-6	5.0E-6
particulates, >2.5 um and <10	air	kg	2.3E-6	3.8E-6	1.8E-6	2.2E-6	4.1E-6	2.9E-6
particulates, <2.5 um	air	kg	1.9E-6	3.5E-6	1.8E-6	5.6E-6	6.4E-6	3.6E-6
Ammonia	air	kg	2.5E-4	8.2E-4	4.0E-6	2.2E-4	6.9E-4	4.2E-4
land occupation	ressource	m2a	4.9E-3	3.7E-4	4.7E-4	4.4E-3	4.4E-4	3.2E-3
cadmium	soil	kg	9.3E-12	5.9E-12	2.4E-12	8.8E-12	1.9E-12	6.9E-12
BOD	water	kg	1.2E-5	2.4E-5	1.1E-5	6.7E-5	7.0E-5	3.4E-5
further LCI results								
N20	air	kg	8.7E-5	8.5E-6	8.2E-6	8.2E-5	1.3E-5	5.9E-5
methane	air	kg	5.3E-4	3.5E-3	6.0E-4	6.2E-4	3.3E-3	1.6E-3
carbon monoxide	air	kg	1.6E-4	2.1E-4	1.3E-4	4.4E-4	4.6E-4	2.8E-4
carbon, biogenic, fixed	air	kg	3.0E-4	-1.2E-6	-2.0E-5	2.7E-4	-1.8E-5	1.8E-4
heat, waste	total	MJ	1.5E+0	1.9E+0	1.1E+0	1.4E+0	1.6E+0	1.5E+0

Tab. 13.30 Selected LCI results and the cumulative energy demand for heat from co-generation with biogas

Name			Heat, at cogen with biogas engine, agricultural covered, allocation exergy	Heat, at cogen with biogas engine, agricultural, allocation exergy	Heat, at cogen with biogas engine, allocation exergy	Heat, at cogen with ignition biogas engine, agricultural covered, alloc. exergy	Heat, at cogen with ignition biogas engine, allocation exergy	Heat, at cogen, biogas agricultural mix, allocation exergy
location			CH	CH	CH	CH	CH	CH
Unit			MJ	MJ	MJ	MJ	MJ	MJ
Infrastructure			0	0	0	0	0	0
energy ressources								
non-renewable								
fossil		MJ Eq	8.4E-3	1.5E-2	9.3E-2	3.8E-2	6.8E-2	2.8E-2
nuclear		MJ Eq	5.3E-3	6.3E-3	3.3E-2	5.4E-3	1.1E-2	6.9E-3
renewable		MJ						
biomass		MJ Eq	1.8E-3	9.5E-5	2.9E-4	1.6E-3	1.7E-4	1.2E-3
wind, solar, geothermal		MJ Eq	3.1E-5	3.6E-5	1.3E-4	3.8E-5	6.7E-5	4.2E-5
water		MJ Eq	2.9E-5	5.1E-5	4.0E-5	2.8E-5	1.0E-4	5.2E-5
selected LCI results								
NMVOC	air	kg	1.1E-6	1.7E-6	3.3E-6	4.2E-6	7.4E-6	3.2E-6
CO2, fossil	air	kg	5.9E-4	1.1E-3	5.3E-3	2.8E-3	5.2E-3	2.1E-3
sulphur dioxide	air	kg	8.4E-6	9.5E-6	1.5E-5	1.2E-5	2.1E-5	1.2E-5
nitrogen oxides	air	kg	6.2E-6	1.1E-5	1.1E-5	3.3E-5	6.0E-5	2.4E-5
particulates >10 um	air	kg	6.3E-7	8.5E-7	1.0E-6	7.4E-7	1.5E-6	9.0E-7
particulates, >2.5 um and <10	air	kg	3.6E-7	5.1E-7	4.6E-7	4.2E-7	8.9E-7	5.3E-7
particulates, <2.5 um	air	kg	2.4E-7	3.8E-7	3.6E-7	6.3E-7	1.2E-6	5.5E-7
Ammonia	air	kg	2.4E-5	7.7E-5	6.8E-7	2.2E-5	1.2E-4	5.5E-5
land occupation	ressource	m2a	4.6E-4	3.8E-5	8.3E-5	4.4E-4	7.9E-5	3.2E-4
cadmium	soil	kg	9.0E-13	5.8E-13	4.4E-13	9.1E-13	3.6E-13	7.2E-13
BOD	water	kg	1.3E-6	2.5E-6	2.0E-6	6.9E-6	1.2E-5	4.9E-6
further LCI results								
N20	air	kg	8.1E-6	8.0E-7	1.4E-6	8.1E-6	2.2E-6	5.8E-6
methane	air	kg	5.0E-5	3.3E-4	1.0E-4	6.2E-5	5.6E-4	2.2E-4
carbon monoxide	air	kg	1.7E-5	2.1E-5	2.4E-5	4.5E-5	8.1E-5	3.7E-5
carbon, biogenic, fixed	air	kg	2.8E-5	-3.6E-7	-3.6E-6	2.7E-5	-3.0E-6	1.6E-5
heat, waste	total	MJ	6.7E-1	7.1E-1	1.3E+0	6.9E-1	1.4E+0	8.8E-1

For either co-generation plant, electricity production shows higher environmental burdens than heat generation. The reason for this is the selection of the exergy value of the two products as allocation factor. A comparison of the two different types of co-generation plant demonstrates considerably higher emissions for the smaller agricultural co-generation unit equipped with an ignition gas engine. For NO_x-emissions of ignition gas engines direct process emissions dominate the cumulative score. It should be noted that the assumed NO_x-emission value represents the Swiss upper limit for co-generation plants using biogas as a feedstock. In contrast, for NO_x-emissions of gas engines it is also the fuel supply that contributes considerably to the final score.

As a consequence of the biogas production in agricultural biogas plant (covered and non covered), see chap. 12.7.4 and 12.11.3 there are differences between the varying production of biogas especially for the emissions of methane, laughing gas and ammonia.

Abbreviations

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen gas
H_2S	hydrogen sulphide, also often referred to as sewer gas
HV	heating value
HHV	higher heating value
kWh	kilowatt-hour
LCI	life cycle inventory
LCIA	life cycle inventory assessment
LHV	lower heating value
LU	livestock unit
N_2	nitrogen gas
Nm^3	normal cubic meter
NO_x	nitrogen oxides
O_2	oxygen gas
ppm	parts-per-million
SO_x	sulphur oxides
UHV	upper heating value (= higher heating value)
Vol. %	percentage volume (equivalent to percentage molar when dealing with gases)

Appendices: EcoSpold Meta Information

Tab. A. 18 Biogas Production Mix

ReferenceFunction	401	Name	biogas, production mix, at storage
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Data represents the production mix of biogas for Switzerland, generated from digestion of sewage sludge and biowaste.
	404	Amount	1
	490	LocalName	Biogas, Produktionsmix, ab Speicher
	491	Synonyms	
	492	GeneralComment	10% of biogas from sewage sludge is generated from co/generation. Biogas from digestion of whey and grass is currently not available in Switzerland and thus excluded from the mix. Also, biogas generated from digestion of manure is excluded, since this is usually used on the biogas production site and not available for other purposes.
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2002
	602	EndDate	2002
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	statistical data representing the production in the year 2002
Geography	663	Text	Data represents conditions in Switzerland
Technology	692	Text	technology mix
Representativene	722	Percent	100
	724	ProductionVolume	540 GWh per year
	725	SamplingProcedure	national statistics
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAnd	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 19 Upgrading of Biogas

ReferenceFunction	401	Name	methane, 96 vol-%, from biogas, at purification
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	Nm3
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Electricity consumption and emissions represent the raw gas compression, H_2S removal, gas conditioning and methane enrichment of biogas. The production and disposal of activated carbon are neglected. Infrastructure expenditures are included employing generic data for facilities of a chemical plant as a first approximation.
	404	Amount	1
	490	LocalName	Methan, 96 Vol.-%, aus Biogas, ab Aufbereitung
	491	Synonyms	
	492	GeneralComment	The data presented is derived from information available from the manufacturer of biogas upgrading plants. The upgraded gas leaves the process with a pressure of 5 bar. For the composition of the product gas we assume a share of 96 Vol. % of methane.
	494	InfrastructureIncluded	0
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2004
	602	EndDate	2005
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	A plant using the described technology is in operation in Switzerland.
Technology	692	Text	Pressure Switch Adsorption (PSA)
Representativene	722	Percent	100
	724	ProductionVolume	Not known
	725	SamplingProcedure	Literature data
	726	Extrapolations	slightly higher electricity consumption as in reference sources.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 20 Co-generation of Biogas from a Production Mix of Biowaste and Raw Sewage Sludge

ReferenceFunction	401	Name	biogas gas, burned in cogen with gas engine
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	MJ
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Use of biogas in a cogeneration unit. Included are emissions to air, biogas consumption, use and disposal of operational supplements as well as infrastructure expenditures.
	404	Amount	1
	490	LocalName	Biogas, in BHKW mit Gasmotor
	491	Synonyms	
	492	GeneralComment	The multioutput process "biogas gas burned in cogen with gas engine" delivers the co-products: heat and electricity. The allocation is based on the exergy values of heat and electricity. The exergy value of electricity is 1, and the exergy value of heat is 0.17. The degrees of efficiency are as follows: electricity: 0.32 and heat: 0.55.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1993
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	Conditions of cogeneration in Switzerland.
Technology	692	Text	Lambda 1-engine" with a catalytic converter
Representativene	722	Percent	100
	724	ProductionVolume	In 2002 the production of electricity from biogas was 9.8 GWh/a.
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

Tab. A. 21 Co-generation of Biogas from Liquid Manure

ReferenceFunction	401	Name	biogas, burned in cogen with ignition gas engine
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	MJ
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	26
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Use of biogas in a cogeneration unit. In addition to biogas also diesel is used as a fuel (0.05 kg diesel per kg biogas). Included are emissions to air, biogas consumption, use and disposal of operational supplements. The calculated emissions include emissions due to the combustion of bio gas and diesel. Infrastructure expenditures are accounted for, too.
	404	Amount	1
	490	LocalName	Biogas, in BHKW mit Zündstrahlmotor
	491	Synonyms	
	492	GeneralComment	The multioutput process "biogas gas burned in cogen with ignition gas engine" delivers the co-products: heat and electricity. The allocation is based on the exergy values of heat and electricity. The exergy value of electricity is 1, and the exergy value of heat is 0.17. The degrees of efficiency are as follows: electricity: 0.33 and heat: 0.54. The value for particle emissions is derived from the current threshold of the German TA-Luft and experiences from practise. The value for NOx-emissions represents the upper Swiss limit for co-generation plants using biogas as feedstock.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	cogeneration
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Wärmekraftkopplung (WKK)
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1993
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	Conditions of co-generation in Switzerland.
Technology	692	Text	50 kWh_{el} lean burn engine
Representativene	722	Percent	100
	724	ProductionVolume	
	725	SamplingProcedure	Literature data
	726	Extrapolations	none
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	26
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	biogas

References

Edelmann et al. 2001	Edelmann W., Schleiss K., Engeli H. and Baier U. (2001) Ökobilanz der Stromgewinnung aus landwirtschaftlichem Biogas - Schlussbericht 2001. Arbi Bioenergy GmBH, Baar, Baar.
Heck 2003	Heck T. (2003) Wärme-Kraft-Kopplung. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Final report ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, CH retrieved from: www.ecoinvent.ch.
Kapdi et al. 2005	Kapdi S. S., Vijay V. K., Rajesh S. K. and Prasad R. (2005) Biogas scrubbing, compression and storage: perspective and prospectus in Indian context. In: Renewable Energy, 30(8), pp. 1195-1202, retrieved from: http://www.sciencedirect.com/science/article/B6V4S-4DV1GJ4-3/2/e3a121fd386004494d81128d18806336.
LRV 2000	LRV (2000) Luftreinhalte-Verordnung vom 16. Dezember 1985 (LRV). (Stand am 28. März 2000). Schweizerischer Bundesrat, Bern, Online-Version unter: http://www.admin.ch/ch/d/sr/c814_318_142_1.html.
RÜTGERS 2004	RÜTGERS (2004) Biogas upgrading with PSA and hydrogen reforming technology. In: Biomass fermentation towards usage in fuel cells (BFCNet). BFC Progress workshop II, Braunschweig, Germany.
Schleiss & Edelmann 2000	Schleiss K. and Edelmann W. (2000) Stromproduktion aus der Feststoff-Vergärung. Bundesamt für Energie und Biogasforum Schweiz,ENET, Baar.

14 Ethanol 99.7 % from biomass

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Last changes: 2007

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14.1 Introduction

Ethanol (CH_3CH_2OH, CAS-No. 64-17-5, synonyms: ethyl alcohol, alcohol spirit, spirit of wine, grain alcohol, absolute alcohol, ethyl hydrate) in its pure form (absolute alcohol) is a clear, colourless liquid. It is miscible in all proportions with water and also with ether, acetone, benzene, and some other organic solvents. Anhydrous alcohol is hygroscopic; at a water uptake of 0.3 – 0.4 %, a certain stability does occur. For this inventory the functional unit is 1 kg of ethanol 100%. The most important chemical and physical properties of ethanol used in this inventory are given here.

Tab. 14.1 Chemical and physical properties of ethanol

Property	Value	Unit	Remarks
Molecular weight [1]	46.07	g mol^{-1}	
Specific gravity [1]	790	kg m^{-3}	at 20 °C
Boiling point [1]	78.39	°C	at normal pressure
Melting point [1]	-114.15	°C	at normal pressure
Heat of combustion, net caloric value (LHV) [2]	28.1	MJ kg^{-1}	
Heat of combustion, gross caloric value (UHV) [2]	31	MJ kg^{-1}	
C	0.52	kg kg^{-1}	
O	0.35	kg kg^{-1}	
H	0.13	kg kg^{-1}	

1 Source: Ullmann 2001b

2 Source: BIN 2004

14.2 Reserves and Resources

Ethanol can be produced in two different ways. Either chemically, by hydration of ethylene, or by fermentation of sugar-containing feeds, starchy feed materials or lignocellulosic materials. According to Ullmann 2004 in Europe 40 % of the ethanol is produced from ethylene and 60 % from biomass. Tab. 14.2 shows the production volumes and the feedstocks of the world production of bioethanol in 2002.

Tab. 14.2 World bioethanol production in 2003

Country	Production (1000 hl)	% of world production[1]	Feedstock[2]
Brazil	143845	52.1	sugar cane
USA	105991	38.4	corn (90%), wheat
EU	18927	6.8	wheat, sugar beets, rye
Others	7551	2.7	grains
World	276334	100	

Sources:

1: Savaiko 2004

2: Novem 2003

14.3 Use

Depending on its water content, preparation, and final use, several ethanol products exist on the market. The 99 % alcohol (often referred to as absolute alcohol) is used extensively for tinctures and pharmaceutical preparations, as a solvent and preservative, as an antiseptic, and in perfume. Ethanol is an important functional component of alcoholic beverages, which are produced by fermentation of fermentable carbohydrates. The fermentation broth itself may constitute (after processing and aging) a beverage, e.g., in the case of beer or wine, or the alcohol can be concentrated from the broth to produce high-alcohol-containing spirits. If the alcohol is used for purposes other than as a beverage, it is denatured by the addition of substances such as methanol, pyridine, formaldehyde, or sublimate. The denatured alcohol is then used by industry and commerce, principally as a solvent, as a raw material for manufacturing chemicals, or as a fuel.

14.4 System Characterisation

This report corresponds to the dataset for the production of **1 kg ethanol 99.7% in H_2O from biomass, at fermentation plant, in Switzerland**. As ethanol can be produced from different resources, several processes were considered. The following processes were modelled:

- sugar beets to fermentation, CH. Multioutput process with ethanol and beet chips as allocated products
- grass to fermentation, CH. Multioutput process with ethanol, grass fibres, and proteins as allocated products
- whey to fermentation, CH. Multioutput process with ethanol, protein concentrate, and yeast paste as allocated products
- ethanol, 95% in H_2O, from sugar beets, at fermentation plant, CH.
- ethanol, 95% in H_2O, from grass, at fermentation plant, at plant, CH
- ethanol, 95% in H_2O, from whey, at fermentation plant, at plant, CH
- ethanol, 99.7% in H_2O, from biomass, at distillation, CH
- ethanol, 99.7% in H_2O, from biomass, at service station, CH
- ethanol plant, CH

All data in the present report are referred to 1 kg ethanol 100%. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air and water. It also includes transportation of the raw materials. For the study transient or unstable operations like starting-up or shutting-down, are not included, but the production during stable operation conditions. Storage and transportation of the final product are also not included. It is assumed that the manufacturing plants are located in an urban/industrial area and consequently the emissions are categorised as emanating in a high population density area. The emissions into water are assumed to be emitted into rivers.

14.5 Sugar beets to fermentation, CH

The ethanol produced from sugar beet can result from various substrates such as the juice, the molasses or the process water used in a sugar factory. In this study the production of ethanol from green juice is considered. The process description and the data are based on data of an ethanol plant of the JPI Company, a Finnish subsidiary company of the Jaakko Pöyry group, which have been published in Fromentin 2000. The information relates to an ethanol production factory with a daily capacity of 400000 litres (either an annual capacity of 120 million litres).

14.5.1 Process description

The ethanol is produced by fermentation of the sugars. In fact sugar is the simplest raw material for ethanol. An enzyme secreted by yeasts, Zymase, transforms these sugars into ethanol and carbon dioxide (CO_2).

$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$

This operation is in reality a very complex reaction, and the use of unsuitable yeasts can generate the formation of various quantities of other substances, like organic glycerine or other acids.

The sugar beets are fed into the slicers where very sharp knives cut them into long noodle-like pieces called cossettes. Emerging from the slicers, the cossettes fall onto a conveyor belt to be weighed and are fed into the diffusion system. Here the sugar is removed from the beets by hot water. The beets are fed into the bottom of the diffuser and are moved upward through the diffuser where they emerge with 2% of the sugar left in them. The spent beets are called wet pulp and processed in presses and dryers to become livestock feed. Hot water is fed into the top of the diffuser and flows down through the beets continuously extracting the sugar from the beets and emerges from the diffuser as sugar water called "raw juice".

The fermentation of the raw juice is processed in a series of consecutive tanks. The green juice is pumped in a continuous way of one tank in another with an average time of residence in each tank of about 4-6 hours. The growth of yeasts during fermentation is controlled by a supply oxygen in the first two tanks, as by a followed nitrogen and phosphorus contribution, in the form of phosphoric acid and urea respectively. The alcohol concentration increases regularly from 6-7% in the first fermenter, to nearly 10% in the third. The temperature is maintained between 33°C and 35°C throughout the process. The concentration of ethanol in the beer produced in the fermentation stages can vary from some percent up to 14%. At this concentration, the Zymase enzyme is denaturated, and the fermentation is stopped.

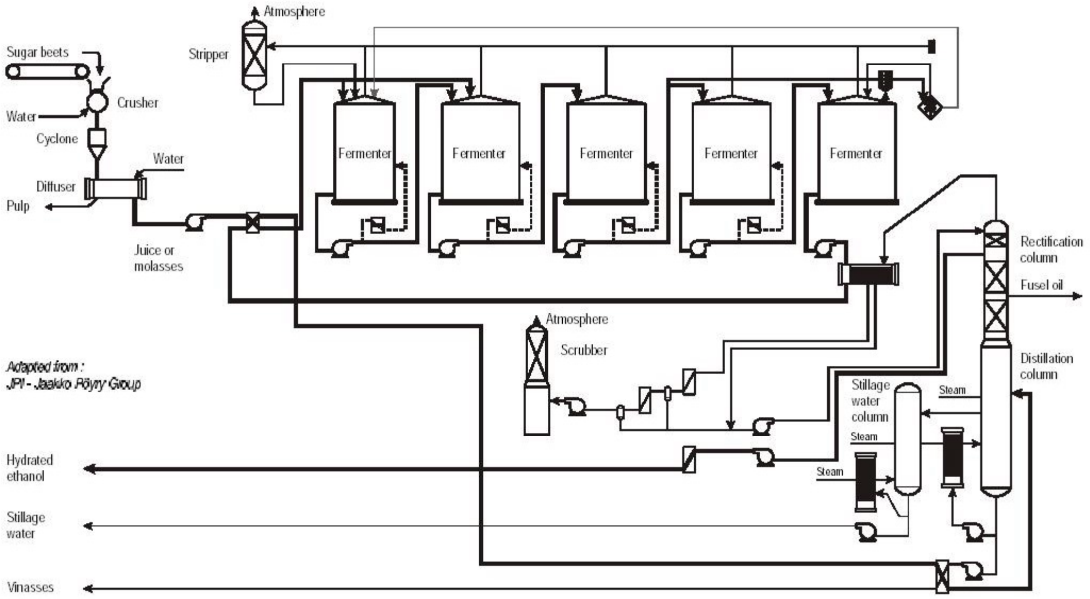

Fig. 14.1 Production of ethanol from sugar beets, fermentation process (taken from Fromentin 2000, Fig. 3.2)

Rectification of ethanol

The rectification of the ethanol is carried out by distillation. Distillation represents a considerable share of the consumption of total energy of the ethanol production. This share is the more important as the alcohol concentration after fermentation is weak. The process of distillation described here is used for the production of alcohol hydrates with 95 %, from fermented beer. The system is composed of three columns, with two columns for concentration, and one column for rectification. The outgoing alcohol vapour from the concentration columns is condensed. In the rectification column the alcohol is concentrated to 95 % m/m. Alcohol is condensed again, then cooled and finally stored in a tank.

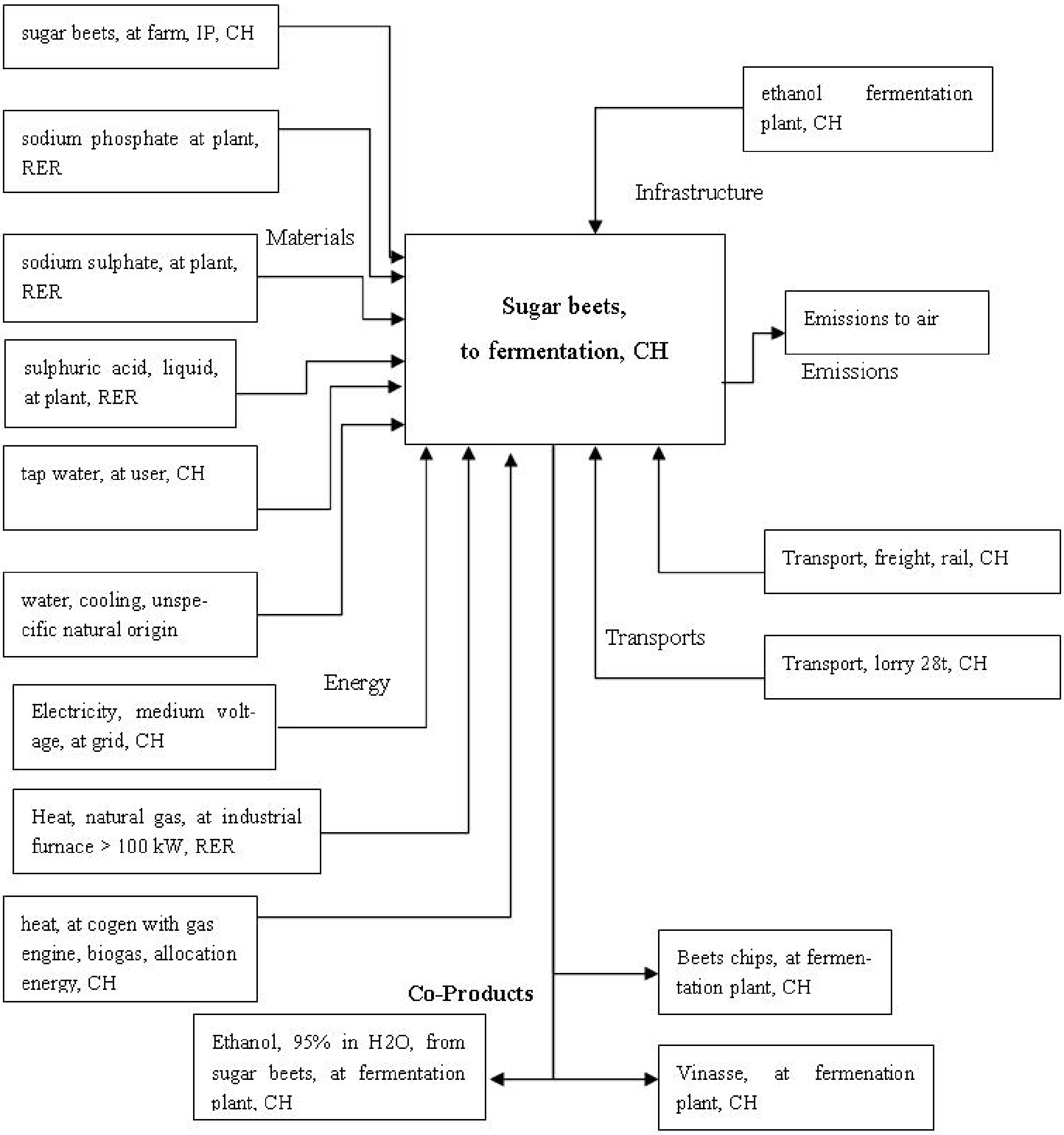

Fig. 14.2 Process flow chart for the production of ethanol from sugar beets

14.5.2 Data sources

The data, which are used in this inventory, are derived from ENERS 2005. In this study the production of ethanol in Switzerland is assessed from various raw materials. Some data are taken from another study (Fromentin 2000).

14.5.3 Raw materials and auxiliaries

Tab. 14.3 shows the values for the use of raw materials and auxiliaries, which are taken from ENERS (2005).

Tab. 14.3 Consumption of raw materials and auxiliaries required for the production of ethanol from sugar beets (ENERS 2005)

Input	per kg ethanol	per kg sugar beets
Sugar beets (kg)	11.53	1
Phosphate (kg)	6.9E-03	5.98E-04
Sulphate (kg)	4.6E-03	3.99E-04
H2SO4 (kg)	3.45E-02	2.99E-03
Process water (kg)	1.1	9.53E-02
Cooling water (kg)	6.03	5.23E-05

14.5.4 Energy

Data for the energy inputs for the fermentation of sugar beets are taken from ENERS 2005. For the steam input the dataset “Heat, natural gas, at industrial furnace > 100 kW, RER” is used. According to Kaltschmidt 1997 a biogas producing wastewater treatment was considered. The biogas is burned and used for process heat. It was considered, that 0.06 MJ heat per kg sugar beets is produced from biogas. It was calculated with the dataset “heat, at cogen with gas engine, biogas, allocation energy, CH. This is a dataset for an allocation product of a cogen, which also produces electricity. In this report no electricity production is considered. Nevertheless this dataset is used for the heat input from biogas, which leads to a little difference.

Tab. 14.4 Energy consumption for the production of ethanol from sugar beets (ENERS 2005, Kaltschmidt 1997)

Input	per kg ethanol	per kg sugar beets
Steam from biogas (MJ)	6.918E-01	6E-02
Heat, natural gas (MJ)	3.797	3.29E-01
Electricity (kWh)	0.213	1.85E-02

1 Values used in this inventory

14.5.5 Transportation

Fromentin (2000) assumes that in contrast to the majority of the countries of the European Union 80% of the Swiss production are transported by rail to the plant. The other 20% are transported by road, in heavy lorries of 28 tons. The average distance between the farm and the factory is about 100 km.

No information is available in the sources consulted concerning transportation of the auxiliaries. Therefore, the following standard distances as defined in Frischknecht 2003 are used: 50 km by lorry 28t and 600 km by train for urea, H_3PO_4, H_2SO_4, antifoam, and NaOH. Tab. 14.5 summarises the total transport amounts for the production of 1 kg ethanol.

Tab. 14.5 Total transport services required for the production of 1 kg ethanol

	tkm kg-1 ethanol	tkm kg-1 sugar beets
lorry	2.33E-01	2.02E-02
train	9.504E-01	8.24E-02

14.5.6 Infrastructure and land use

The infrastructure is estimated based on the dataset "ethanol fermentation plant, CH". This dataset assumes a built area of about 3.75 ha, an average output of 90'000 t/a, and plant life of twenty years. For this study, the estimated value is 5.56 E-10 units per kg of produced ethanol.

14.5.7 Emissions to air

It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

The only emission to air, which is considered, is the emissions of CO_2 from the fermentation and the wastewater treatment. It is calculated from the carbon balance.

The carbon content of the beet chips (25 % dry matter) was assumed as 0.44 kg per kg dry matter, and the carbon content of the vinasse (2.5 % dry matter) was calculated as 0.12867 kg per dry matter according to Stemme 2005.

Tab. 14.6 Process emissions to air from the production of 1 kg ethanol from sugar beets

Output	per kg ethanol	per kg sugar beets
Waste heat (MJ)[1]	0.7668	6.65E-02
Carbon dioxide, biogenic, to air (kg)[2]	0.96	0.084

1: calculated from the electricity input

2: calculated from the carbon balance

14.5.8 Emissions to water

According to Kaltschmidt 1997 no emissions to water are assessed because of the recyling of the process water and the biogas producing wastewater treatment. All organic residues are ended up in the vinasse, which is used as a fertilizer (Fromentin 2000).

14.5.9 Allocation of the co-products of the ethanol production

Within the production of ethanol from sugar beets, beet chips (25 % dry matter) and vinasse (synonym: stillage, 2.5 % dry matter) are obtained as co-products. The beets chips are pressed and sold as animal food. The vinasse is sold as fertilizer. The yields of the co-products and three possible allocation parameters are given in Tab. 14.7. In this inventory the economic value is used. Vinasse is also calculated as co-product, therefor the values are taken from Fromentin (2000). In ENERS (2005) vinasse is not assessed as co-product. The inputs and outputs of the several process steps are allocated in different ways: The pre-treatment is allocated to ethanol, vinasse, and beets chips. The fermentation is allocated to ethanol and vinasse. Pulp pressing is allocated to the beet chips. The CO2-emissions are allocated according to the C-content of the products. The transports of the raw materials are allocated to all products, the transports of the auxilliaries are allocated to ethanol and vinasse In Tab. 14.8 the calculated allocation parameters for the whole process route are given.

Tab. 14.7 Possible allocation parameters of the co-products from the ethanol production from sugar beets

Co-products	Mass factor: yield (kg per kg ethanol)[1]	Heating value (MJ/kg)[2]	Economic value (CHF/kg)[1]	Economic value (CHF/kg)[3]
Beets chips	1.88	14.42	*	0.12
Vinasse	7.146	0.693	0	0.02
Ethanol	1	28.1	*	0.7

Sources:

1: ENERS 2005

2: Kaltschmitt 1997

3: Fromentin 2000

*: Economic allocation: ethanol 95.1 %, beet chips 4.9 %

Tab. 14.8 Allocation factors for the products of the ethanol production from sugar beets

		Ethanol	Beets chips	Vinasse
Inputs	Sugar beets	65.5	21.1	13.4
	Phosphate	83.0	0	17.0
	Sulphate	83.0	0	17.0
	Sulphuric acid	83.0	0	17.0
	Process water	74.6	10.2	15.2
	Cooling water	65.5	21.1	13.4
	Electricity	69.6	16.2	14.2
	Steam	83.0	0	17.0
	Transport lorry	65.7	20.9	13.4
	Transport rail	66.0	20.5	13.5
	Ethanol plant	83.0	0	17.0
Output	Waste heat	69.6	16.2	14.2
	CO2	54.5	2.7	42.8

14.5.10 Life cycle inventory of ethanol production from sugar beets and data quality considerations

Tab. 14.9 shows the data quality indicators for the inventory of the fermentation of sugar beets. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.9 Unit process raw data for the fermentation of sugar beets

	Name	Location	InfrastructureProcess	Unit	sugar beets, to fermentation	UncertaintyType	StandardDeviation95%	GeneralComment	ethanol, 95% in H2O, from sugar beets, at fermentation plant	beet chips, at fermentation plant	vinasse, at fermentation plant
	Location				CH				CH	CH	CH
	InfrastructureProcess				0				0	0	0
	Unit				kg				kg	kg	kg
allocated	ethanol, 95% in H2O, from sugar beets, at fermentation plant	CH	0	kg	8.67300E-2				100.000	-	-
products	beet chips, at fermentation plant	CH	0	kg	1.63053E-1				-	100.000	-
	vinasse, at fermentation plant	CH	0	kg	6.19775E-1				-	-	100.000
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	5.23360E-8	1	1.12	(1,3,1,1,1,4); Eners 2005	65.511	21.113	13.376
technosphere	sugar beets IP, at farm	CH	0	kg	1.00000E+0	1	1.12	(1,3,1,1,1,4); Eners 2005	65.511	21.113	13.376
	sodium phosphate, at plant	RER	0	kg	5.98010E-4	1	1.12	(1,3,1,1,1,4); Eners 2005	83.045	-	16.955
	sodium sulphate, from natural sources, at plant	RER	0	kg	3.98700E-4	1	1.12	(1,3,1,1,1,4); Eners 2005	83.045	-	16.955
	tap water, at user	CH	0	kg	9.53200E-2	1	1.12	(1,3,1,1,1,4); Eners 2005	83.045	-	16.955
	sulphuric acid, liquid, at plant	RER	0	kg	2.99219E-3	1	1.12	(1,3,1,1,1,4); Eners 2005	83.045	-	16.955
	transport, lorry 28t	CH	0	tkm	2.02082E-2	1	2.09	(4,5,na,na,na,na); Fromentin 2000; Standard distances	65.684	20.905	13.411
	transport, freight, rail	CH	0	tkm	8.24285E-2	1	2.09	(4,5,na,na,na,na); Fromentin 2000; Standard distances	66.020	20.500	13.480
	electricity, medium voltage, at grid	CH	0	kWh	1.84736E-2	1	1.12	(1,3,1,1,1,4); Eners 2005	69.560	16.238	14.202
	heat, at cogen with biogas engine, allocation exergy	CH	0	MJ	6.00000E-2	1	1.15	(1,1,3,1,1,4); Kaltschmidt 1997	83.045	-	16.955
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	3.29315E-1	1	1.12	(1,3,1,1,1,4); Eners 2005	83.045	-	16.955
	ethanol fermentation plant	CH	1	unit	4.44000E-11	1	3.09	(2,4,1,5,3,4); Estimation	65.511	21.113	13.376
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	8.35595E-2	1	1.24	(4,3,1,1,1,4); Calculated from the carbon balance	54.548	2.657	42.795
emission air, high population density	Heat, waste	-	-	MJ	6.65048E-2	1	1.24	(4,3,1,1,1,4); Calculated from the electricity input	69.560	16.238	14.202

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	sugar beets, to fermentation
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Fermentation of sugar beets including materials, energy uses, infrastructure, and emissions.
	404	Amount	1
	490	LocalName	Zuckerrüben, in Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput-process "sugar beets, to fermentation" delivers the co-products Ethanol, 95% in H20, from sugar beets", "beets chips", and vinasse. The allocation is based on economic criteria. World production of ethanol from sugar beets is around 10 Mio hl per year.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled with data from a plant in Finland.
Technology	692	Text	Production of ethanol from sugar beets with extraction, fermentation, and distillation of ethanol.
Representativene	722	Percent	12
	724	ProductionVolume	The world production of ethanol from sugar beets is around 10 Mio hl per year.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

14.6 Grass, to fermentation, CH

Ethanol can be produced from the lignocellulosic biomass such as wood or grass (Wyman 1992). The resource selected in this inventory is grass. The industrial process of transformation retained in this chapter is based on the production of ethanol by the company 2B AG, situated at Märwil, which carries out the grass transformation into bioethanol in a pilot unit of an annual capacity of 1.4 million litres of ethanol.

The principal components of grass are primarily the cellulose and hemicellulose. The chemical composition varies appreciably according to categories of grass considered, the season, the type of ground as well as the weather conditions. In this inventory the grass of meadow (45 % cellulose, 29 % hemicellulose, 26 % others) will be used. The celluloses contained in the plants are in a crystalline form with very strong connections, which reduces the possibility of enzymatic disintegration. The technique making it possible to improve the digestibility of cellulose consists of increasing the surface accessible to the enzymes by carrying out pre-hydrolysis. Hemicellulose is thus separated in order to increase the size of the active sites, thus allowing the enzymatic attack. Today there is a variety of methods of dissolution, of extraction and of hydrolysis of the lignocellulosic biomass succeeding to fermentable sugars. These enzymatic processes include four stages: pre-treatment, production of enzymes, the hydrolysis and the fermentation. The most current processes are referenced in the following way: saccharification and simultanous fermentation (SSF); acid hydrolysis, neutralization and fermentation (AHNF); disintegration with ammonia, hydrolysis and fermentation (AHF); disintegration with steam, hydrolysis and fermentation (SHF). The SSF process is often considered as the most rational technique for the production of ethanol from grass (Wyman 1992). It is considered in this study.

14.6.1 Process description

Pre-treatment

The purpose of the pre-treatment with steam is to destroy the crystalline structure of cellulose in order to extract cellulose and hemicellulose and to make the enzymatic disintegration in the following stage thus more effective. This method is of interest, because it is relatively simple and the proteins contained in the grass are not destroyed; which represents a considerable economic benefit for the process.

Saccharification and simultanous fermentation

Following the pre-treatment, the specific use of enzymes or microorganisms allows to release the sugars from the cellulose (glucose, fructose) and from the hemicellulose (xylose). These simple sugars are then fermented to ethanol with the help of yeasts.

$-(\mathrm{C_6H_{10}O_6})- + \mathrm{H_2O}$	→	$n\ \mathrm{C_6H_{10}O_6}$
Cellulose	Hydrolysis	Glucose
$\mathrm{C_6H_{10}O_6}$	→	$2\ \mathrm{C_2H_5OH} + 2\ \mathrm{CO_2}$
Glucose	Fermentation	Ethanol

Thus, the fermentation of one molecule of glucose produces 2 molecules ethanol. In the same way it is possible to extract the xylose from the hemicellulose, from which ethanol can be produced. Before being fed into the distillation unit, the beer which results from the fermentation undergoes two consecutive stages of solid-liquid separation. The beer is first of all filtered in order to withdraw the fibres, then decanted to extract the proteins.

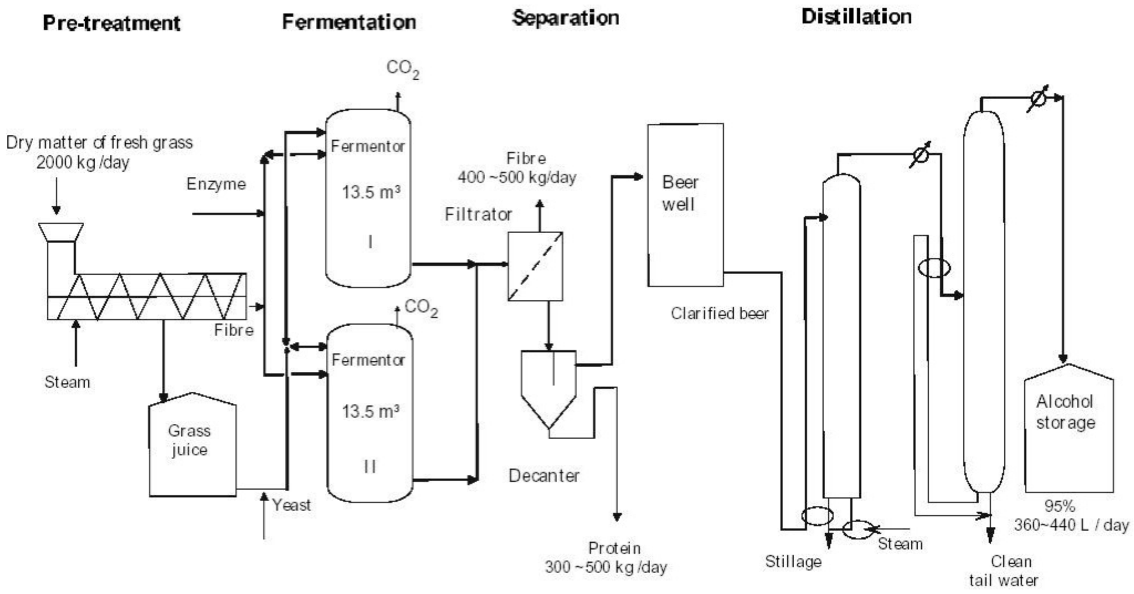

Fig. 14.3 Process chart of the production of ethanol from grass (taken from Fromentin 2000, Fig. 3.5)

Covering of the ethanol

The beer is transferred to the distillation unit, which separates the ethanol from the residual vinasses. The ethanol is concentrated by distillation up to 95 % (ethanol hydrate). The process is the same as described in Chapter 7.5.

Steam production

The residual liquids can be transported back by the farmer who delivers the grass. It can be used as supplement to the fertilization of the field. However, in spite of the relatively low calorific value, this quantity of residual liquids represents a potential usable energy. This liquid, with a temperature of 60-80°C, constitutes in fact an ideal substrate for the production of biogas. Also, in order to determine the real potential of the use of grass, a production of biogas from the residual liquids has been taken into account. This biogas is brought into a boiler to produce steam, which is used in the stages of the ethanol production. The potential has been evaluated in the following way: the volume of biogas produced in the engine is assumed as 1.18 m^3 per litre of ethanol (Fromentin 2000). Knowing that biogas possesses a calorific value of 21.6 MJ/m^3, the quantity of energy amounts 25.5 MJ. This biogas, constituting of a mixture of CH_4 (70%) and CO_2 (30%), is brought into a boiler (with an thermal efficiency of 90%) to produce steam. The quantity of energy available in the form of steam is thus of 22.9 MJ, that is to say 9.0 kg of steam per litre of ethanol. This steam is used for the energy consumption of the various stages of production.

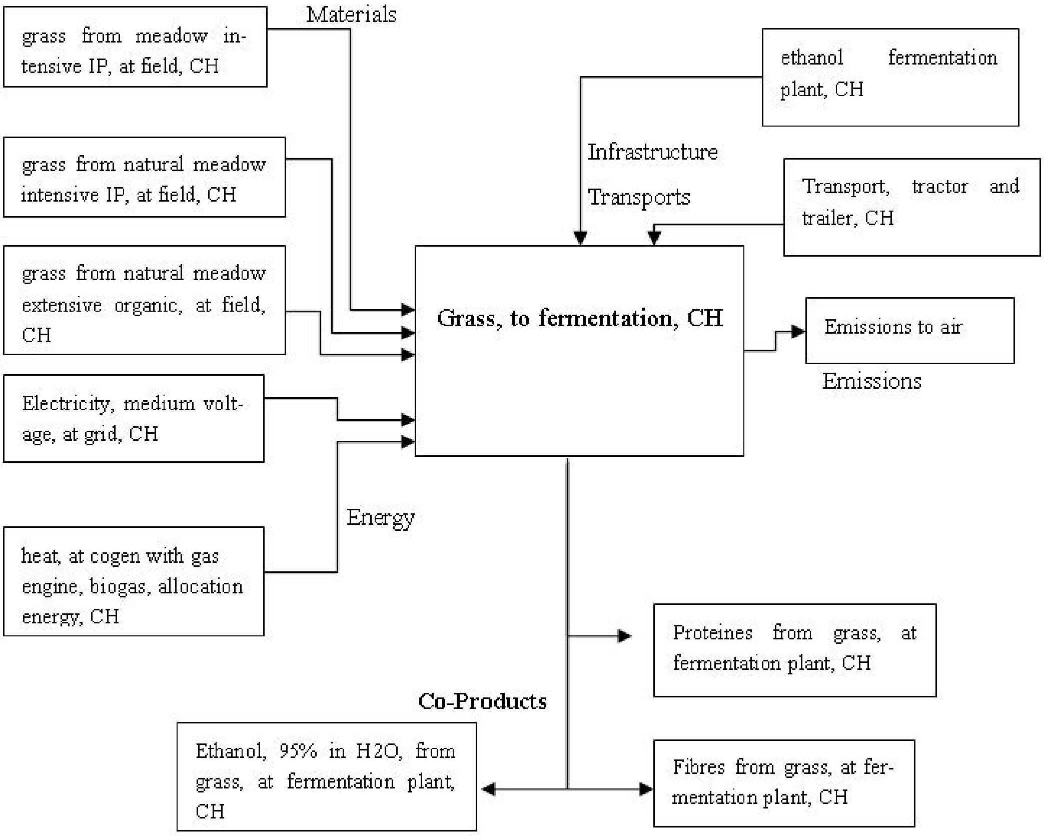

Fig. 14.4 Process flow chart for the grass fermentation

14.6.2 Raw materials and auxiliaries

No information is available concerning the use of the enzymes and yeasts. Therefore, these auxiliaries are neglected. The grass input is calculated as kg dry mass with 15 % dry mass per kg grass.

Tab. 14.10 Consumption of raw materials and auxiliaries for the grass fermentation (Fromentin 2000)

Input	per kg ethanol	per kg grass
Grass (kg)	8.074	1

According to Oettli 2004 the grass mix in Switzerland is calculated with the values, which are given in Tab. 14.11.

Tab. 14.11 Grass mix, Switzerland (Source: Oettli 2004)

Input	%
grass from meadow intensive IP, at field, CH	32.4
grass from natural meadow intensive IP, at field, CH	61.5
grass from natural meadow extensive organic, at field, CH	6.1

14.6.3 Energy

The energy inputs for the fermentation of grass are taken from Fromentin 2000. For the steam input the dataset "heat, at cogen with gas engine, biogas, allocation energy, CH" is used. "Heat, at cogen with gas engine, biogas, allocation energy, CH" is a dataset for an allocation product of a cogen, which also produces electricity. In this report no electricity production is considered. Nevertheless this dataset is used for the heat input from biogas, which leads to a little difference.

Tab. 14.12 Energy consumption for the grass fermentation

Input	Total per kg ethanol1	Total per kg grass
Steam from biogas (MJ)	28.3	3.51
Electricity (kWh)	2.52	0.31

1 Source: Fromentin 2000

14.6.4 Transportation

As an approximation the transport of the grass to the ethanol plant is estimated as 10 km by lorry, 16 t according to Fromentin 2000.

Tab. 14.13 Total transport amounts for the grass fermentation

Total transports	tkm kg-1 ethanol	tkm kg-1 grass
Lorry, 16t	0.54	0.067

14.6.5 Infrastructure and land use

The infrastructure is estimated based on the dataset "ethanol fermentation plant, CH". This dataset assumes a built area of about 3.75 ha, an average output of 90'000 t/a, and plant life of twenty years. For this study, the estimated value is 5.56 E-10 units per kg of produced ethanol.

14.6.6 Emissions to air

It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

The only emission to air, which is considered, is the emission of CO_2 from the fermentation and the wastewater treatment. It was calculated from the carbon balance.

The carbon content of the fibres was assumed as 0.44 kg per kg dry matter, and the carbon content of the proteins was calculated as 0.4 kg per kg dry matter (according to Nemecek 2004).

Tab. 14.14 Process emissions to air from the grass fermentation

Output	per kg ethanol	per kg grass
Waste heat (MJ)[1]	9.07	1.12
Carbon dioxide, biogenic, to air (kg)[2]	5.85	0.74

1: calculated from the electricity input

2: calculated from the carbon balance

14.6.7 Emissions to water

According to Fromentin (2000) no emissions to water are considered because of the recyling of the process water. The organic residues are ended up in the stillage, which is treated in a wastewater plant. The produced biogas is burned and used as heating gas for the distillation unit.

14.6.8 Allocation of the co-products of the ethanol production

Within the production of ethanol from grass, fibres and proteins are obtained as co-products. The fibres represent the lignocellulosic matter, which has not been converted during the process. These fibres constitute a thermic insulator of very good quality. They can also be used for the specific production of polymers or of resins. The proteins are used (after drying also) like substitute in animal feeding. In other balances these co-products are burned to get energy (ENERS 2005). In this dataset they are considered as co-products, which are sold. The yields of the co-products are given in Tab. 14.15. As allocation factor the economic value is used according to Fromentin 2000. The inputs and outputs of the several process steps are allocated in different ways: The pre-treatment is allocated to ethanol, proteins, and fibres. The fermentation is allocated to ethanol and proteins. The distillation is allocated to ethanol. The CO2-emissions are allocated according to the C-content of the products. The transports of the raw materials are allocated to all products. In Tab. 14.17 the calculated allocation factors for the whole process route are given

Tab. 14.15 Yields of the co-products from the grass fermentation (Fromentin 2000)

Co-products	kg per kg ethanol
Fibres (dry mass)	1.62
Proteins (dry mass)	2.01

Tab. 14.16 Economic values of the co-products from grass fermentation (Fromentin 2000)

Co-products	Economic value (CHF/kg)
Fibres	1
Proteins	0.6
Ethanol	0.7

Tab. 14.17 Allocation factors for the products of the grass fermentation

Inputs/Outputs	Ethanol	Proteins	Fibres
Grass	19.9	34.2	45.9
Electricity	25.8	47.5	26.7
Steam	54.3	27.1	18.6
Transport	20.0	35.4	44.6
Ethanol plant	20.0	35.4	44.6
CO2	12.7	27.6	59.6
Waste heat	35.0	50.0	15.0

14.6.9 Life cycle inventory of ethanol production from grass and data quality considerations

Tab. 14.18 shows the data quality indicators of the inventory of the fermentation of grass. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.18 Unit process raw data for the fermentation of grass

	Name	Location	InfrastructureProcess	Unit	grass , to fermentation	UncertaintyType	StandardDeviation95%	GeneralComment	ethanol, 95% in H2O, from grass, at fermentation plant	grass fibres, at fermentation	proteins from grass, at fermentation
	Location				CH				CH	CH	CH
	InfrastructureProcess				0				0	0	0
	Unit				kg				kg	kg	kg
allocated	ethanol, 95% in H2O, from grass, at fermentation plant	CH	0	kg	1.23853E-1				100.000	-	-
products	grass fibres, at fermentation	CH	0	kg	2.00306E-1				-	100.000	-
	proteins from grass, at fermentation	CH	0	kg	2.49236E-1				-	-	100.000
technosphere	grass from meadow intensive IP, at field	CH	0	kg	3.24000E-1	1	1.12	(1,3,1,1,1,4); Frometin 2000	19.860	45.884	34.256
technosphere	grass from natural meadow intensive IP, at field	CH	0	kg	6.15000E-1	1	1.12	(1,3,1,1,1,4); Frometin 2000	19.860	45.884	34.256
technosphere	grass from natural meadow extensive IP, at field	CH	0	kg	6.10000E-2	1	1.12	(1,3,1,1,1,4); Frometin 2000	19.860	45.884	34.256
	transport, lorry 16t	CH	0	tkm	6.66667E-2	1	2.06	(4,1,1,1,1,4); Fromentin 2000	19.860	45.884	34.256
	heat, at cogen with biogas engine, allocation exergy	CH	0	MJ	3.50918E+0	1	1.11	(1,1,1,1,1,4); Frometin 2000	54.295	18.604	27.101
	electricity, medium voltage, at grid	CH	0	kWh	3.11927E-1	1	1.11	(1,1,1,1,1,4); Frometin 2000	25.780	26.683	47.537
	ethanol fermentation plant	CH	1	unit	4.95000E-11	1	3.09	(2,4,1,5,3,4); Estimation	19.860	45.884	34.256
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	7.36515E-1	1	1.24	(4,1,1,1,1,4); calculated from the carbon balance	12.736	59.625	27.639
emission air, high population density	Heat, waste	-	-	MJ	1.12294E+0	1	1.24	(4,1,1,1,1,4); Calculated from the electricity input	25.780	26.683	47.537

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	grass , to fermentation
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Fermentation of grass including materials, energy uses, infrastructure, and emissions.
	404	Amount	1
	490	LocalName	Gras, in Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput-process "grass, to fermentation" delivers the co-products Ethanol, 95% in H20, from grass", "fibres from grass", and "proteins from grass". The allocation is based on economic criteria. The production of ethanol from grass is of no economical importance in the world.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	production
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled with data from a pilot plant in Switzerland.
Technology	692	Text	Production of ethanol from grass with the Saccharification and Simultanous Fermentation process.
Representativene	722	Percent	100
	724	ProductionVolume	The production of ethanol from grass in Switzerland was 15000 hl in 2000.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

14.7 Whey, to fermentation, CH

Whey is an ideal substrate for the production of bioethanol, and several installations on large scale were designed in countries, which have an important lacteal industry, such as Ireland, the USA or New Zealand, where 50 % of the whey is used to produce ethanol.

The Carbery process, currently used in Ireland, which is chosen for this study, produces nearly 6.8 million litres of ethanol per year. Fermentation is realised in engines of a capacity of 160 m^3, with a time of residence of 18-20 hours. The concentration of ethanol obtained by fermentation of the raw whey does not exceed 2-3%. The installation batches 400000 litres of whey per day. Whey is the principal by-product of the production of cheese. It represents 80-90 % of the total volume of milk, and retains 50% of the dry matter. Its composition varies according to the techniques applied for the production of the various cheese products. The typical composition of the whey is water (93.6 %), lactose (4.9 %), proteins (0.8), lipids (0.5 %), other (0.2 %) (Fromentin 2000).

The ethanol is biologically produced according to the following reaction:

$C_{12}H_{22}O_{11} + H_2O \rightarrow 4\ C_2H_5OH + 4\ CO_2$

Lactose Ethanol

Pre-treatment

As the reaction indicates, only the lactose is used for the production of ethanol. Thus, it is preferable to pre-treat whey e.g. by ultrafiltration in order to separate the proteins (8 kg/m^3) which is used as an admixture of animal feeding. This stage constitutes the phase of pre-treatment. The proteins contained in whey possess a high value of digestibility and can be separated from the liquid by ultrafiltration. One recovered product is the concentrated protein; another one is the residual liquid whose principal component is the lactose. The filtration does not remove the lipids from the whey, because they are essential for the continuation of the process, and in particular to ensure the fermentation of sugars. The filtrate can be used directly as substrate for fermentation, after correction of the pH. The anaerobic fermentation using specific yeasts makes it possible to reach a concentration of 2-4% of ethanol. This implies an important consumption of energy to ensure covering by distillation from the beer. This process, which is the most important, is represented in .

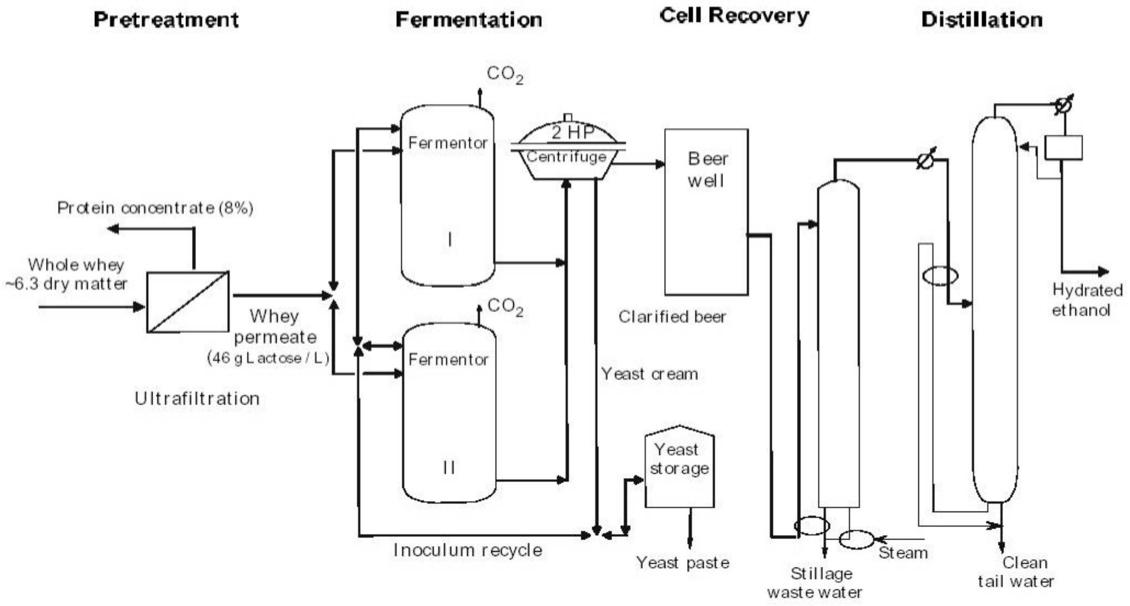

Fig. 14.5 Production of ethanol from whey (taken from Fromentin 2000, Fig. 3.10)

Fermentation

The fermentation of the whey to produce ethanol can be done by different processes. In this study the process considered uses *Kluyveromyces fragilis*; that is the micro-organism of choice in the majority of the commercial installations. In the fermentation, this yeast uses the lactose contained in raw whey with an effectiveness of conversion of 80-85% compared to the theoretical value of 0.538 kg ethanol per kg of lactose.

Covering of the ethanol

The beer, which results from the fermentation process, is then transferred towards the distillation unit, which separates the ethanol from the residual liquids. The ethanol is thus concentrated until 95 % (ethanol hydrate) by distillation. The process is the same as described in the report for sugar beets, to fermentation, CH.

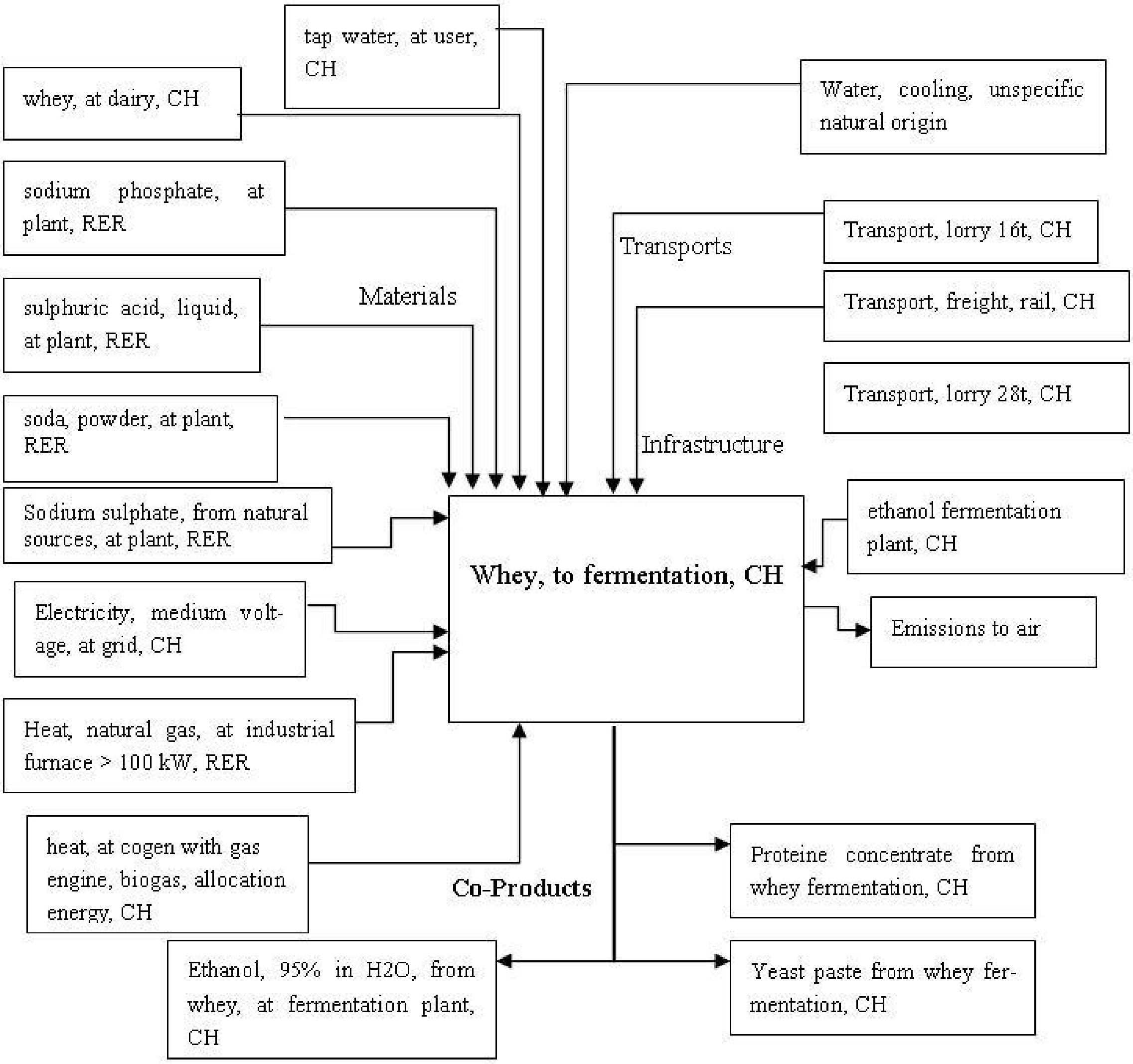

Fig. 14.6 Process flow chart for the production of ethanol from whey

14.7.1 Raw materials and auxiliaries

The inputs for soda, sulphate, and phosphate are calculated with the datasets “soda, powder, at plant, RER”, “sodium sulphate, from natural sources, at plant, RER”, and “sodium phosphate, at plant, RER”.

Tab. 14.19 Consumption of raw materials and auxiliaries for the production of ethanol from whey

Input	Pre-treatment (per kg ethanol)[1]	Fermentation (per kg ethanol)[1]	Total per kg ethanol	Total per kg whey
Whey (kg)	57.08		57.08	1
Soda (kg)	0.0111	0.03461	0.04571	8.01E-04
H2SO4 (kg)	0.00318	0.02215	0.02533	4.44E-04
Sulphate (kg)		0.00222	0.00222	3.89E-05
Phosphate (kg)		0.00581	0.00581	1.02E-.04
Cooling water (kg)	10.138		10.138	2.52E-02
Process water (kg)		6.71	6.71	1.18E-01

1 Source: ENERS 2005

14.7.2 Energy

The energy inputs for the fermentation of whey are taken from ENERS 2005. For the heat input from the biogas from the wastewater treatment the dataset “heat, at cogen with gas engine, biogas, allocation energy, CH“ is used. The remaining heat input is calculated with the dataset “Heat, natural gas, at industrial furnace > 100 kW, RER”. “Heat, at cogen with gas engine, biogas, allocation energy, CH” is a dataset for an allocation product of a cogen, which also produces electricity. In this report no electricity production is considered. Nevertheless this dataset is used for the heat input from biogas, which leads to a little difference.

Tab. 14.20 Energy consumption for the production of 1 kg ethanol

Input	Total per kg ethanol[1]	Total per kg whey
Heat, natural gas (MJ)	7.06261	1.24E-01
Steam from biogas (MJ)	3.85155	6.75E-02
Electricity (kWh)	0.41692	7.30E-03

1 Source: ENERS 2005

14.7.3 Transportation

The transport of the whey to the ethanol plant is calculated as 100 km by lorry, 16 t (ENERS 2005). No information is available in the sources consulted concerning transportation of the auxiliaries. Therefore, the following standard distances as defined in Frischknecht 2003 are used: 50 km by lorry 28t and 600 km by train for the NaOH. Tab. 14.21 summarises the total transport services required for the production of 1 kg ethanol.

Tab. 14.21 Total transport services required for the production of 1 kg ethanol

Total transports	tkm kg^{-1} ethanol	tkm kg^{-1} whey
Lorry 16t	5.708	1E-01
Lorry 28t	2.85E-03	4.99E-05
rail	3.42E-02	5.99E-04

14.7.4 Infrastructure and land use

The infrastructure is estimated based on the dataset "ethanol fermentation plant, CH". This dataset assumes a built area of about 3.75 ha, an average output of 90'000 t/a, and plant life of twenty years. For this study, the estimated value is 5.56 E-10 units per kg of produced ethanol.

14.7.5 Emissions to air

It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

The only emission to air, which is considered, is the emissions of CO_2 from the fermentation and the wastewater treatment. It is calculated from the carbon balance.

The carbon content of the proteins (8% dry matter) is calculated with 0.474 kg per kg dry matter and the carbon content of the yeast paste (20% dry matter) is calculated as 0.4 kg per kg dry matter (according to Nemecek 2004).

Tab. 14.22 Process emissions to air from the production of 1 kg ethanol from whey

Output	Per kg ethanol	Per kg whey
Waste heat (MJ)[1]	1.5009	2.63E-02
Carbon dioxide, biogenic, to air (kg)[2]	2.87	5.03E-02

1: calculated from the electricity input

2: calculated from the carbon balance

14.7.6 Emissions to water

As no other data are available from ENERS (2005), the emissions to water are thus calculated: Fromentin (2000) reports that 15 % of the lactose input leaves the production process with the wastewater. It is assumed that this wastewater is treated in an internal biogas producing wastewater plant. The removal efficiency for lactose was assumed with 90%. The carbon contained in the removed lactose was accounted as CO_2 emissions to air. The values for COD, BOD, TOC, and DOC used in this inventory were calculated from the amount of lactose in the treated wastewater assuming a carbon conversion of 96% for COD. For the calculation of the values for BOD and DOC the worst-case scenario BOD = COD and TOC = DOC was used. A summary of the values used in this inventory is given in Tab. 14.23.

Tab. 14.23 Process emissions to water from the production of ethanol from whey

Output	Value	Remarks
COD, BOD (kg)	7.88E-04	calculated from water emissions
TOC, DOC (kg)	3.15E-04	calculated from water emissions

14.7.7 Allocation of the co-products of the ethanol production

Within the production of ethanol from whey, protein concentrate (8 % dry matter) and yeast paste (20 % dry matter) are obtained as co-products. The yeast paste can be used for human consumption; the protein concentrate can be used for animal food. The yields of the co-products are given in Tab. 14.24. In this inventory the economic value is used as allocation factor. Yeast paste is also calculated as co-product, therefor the values are taken from Fromentin (2000). In ENERS (2005) yeast paste is not assessed as co-product. The inputs and outputs of the several process steps are allocated in different ways: The ultrafiltration is allocated to ethanol, protein, and yeast paste. The fermentation is allocated to ethanol and yeast paste. The air and water emissions are allocated according to the C-content of the products. The transports of the raw materials are allocated to all products, the transports of the auxilliaries are allocated to ethanol and yeast paste. InSources:

1: Calculated from ENERS 2005

2: ENERS 2005

3: Fromentin 2000

*: Economic allocation: ultrafiltration protein concentrate 100%, other processes ethanol 100%

Tab. 14.26 the calculated allocation factors for the whole process route are given.

Tab. 14.24 Yields of the co-products from the ethanol production from whey (ENERS 2005)

Co-products	kg per kg ethanol
Proteins	5.927
Yeast paste [1]	1.144

1: In ENERS 2005 yeast paste is not calculated as co-product.

Tab. 14.25 Possible allocation parameters of the co-products from the ethanol production from whey (Fromentin 2000, ENERS 2005)

Co-products	Mass allocation Factor [1]	Energy content (MJ/kg) [2]	Economic value (CHF/kg) [2]	Economic value (CHF/kg) [3]
Proteins	73.4	17.67	*	0.44
Yeast paste	14.2	1.49	na	2.2
Ethanol	12.4	28.1	*	0.7

Sources:

1: Calculated from ENERS 2005

2: ENERS 2005

3: Fromentin 2000

*: Economic allocation: ultrafiltration protein concentrate 100%, other processes ethanol 100%

Tab. 14.26 Allocation factors for the products of the ethanol production from whey

Input/Output	Ethanol	Protein	Yeast paste
Whey	12.8	41.1	46.1
Soda	21.6	0.9	77.5
Sulphuric acid	21.2	2.6	76.2
Sulphate	21.8	0	78.2
Phosphate	21.8	0	78.2
Cooling water	17.2	20.9	61.9
Process water	21.8	0	78.2
Electricity	19.2	11.7	69.1
Steam	21.5	1.1	77.4
Transport lorry 16 t	12.8	41.1	46.1
Transport lorry 28 t	21.2	2.6	76.2
Transport rail	21.2	2.6	76.2
Ethanol plant	12.8	41.1	46.1
Waste heat	19.2	11.7	69.1
CO2	-41.5	63.9	77.6
COD, COD	12.8	41.1	46.1
TOC, DOC	12.8	41.1	46.1

14.7.8 Life cycle inventory of ethanol production from whey and data quality considerations

Tab. 14.27 shows the data quality indicators for the inventory of the fermentation of whey. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.27 Unit process raw data for the fermentation of whey

	Name	Location	InfrastructureProcess	Unit	whey , to fermentation	UncertaintyType	StandardDeviation95%	GeneralComment	ethanol, 95% in H2O, from whey, at fermentation plant	protein concentrate, from whey, at fermentation	yeast paste, from whey, at fermentation
	Location				CH				CH	CH	CH
	InfrastructureProcess				0				0	0	0
	Unit				kg				kg	kg	kg
allocated	ethanol, 95% in H2O, from whey, at fermentation plant	CH	0	kg	1.75193E-2				100.000	-	-
products	protein concentrate, from whey, at fermentation	CH	0	kg	1.03837E-1				-	100.000	-
	yeast paste, from whey, at fermentation	CH	0	kg	2.00420E-2				-	-	100.000
technosphere	whey, at dairy	CH	0	kg	1.00000E+0	1	1.12	(1,1,1,3,1,4); Eners 2005	12.018	44.773	43.209
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	2.51600E-5	1	1.12	(1,1,1,3,1,4); Eners 2005	17.213	20.901	61.886
	tap water, at user	CH	0	kg	1.17554E-1	1	1.12	(1,1,1,3,1,4); Eners 2005	21.761	-	78.239
	sodium sulphate, from natural sources, at plant	RER	0	kg	3.88930E-5	1	1.12	(1,1,1,3,1,4); Eners 2005	21.761	-	78.239
	sodium phosphate, at plant	RER	0	kg	1.01790E-4	1	1.06	(1,1,2,2,1,3); Eners 2005	21.761	-	78.239
	soda, powder, at plant	RER	0	kg	8.00810E-4	1	1.12	(1,1,1,3,1,4); Eners 2005	21.560	0.925	77.515
	sulphuric acid, liquid, at plant	RER	0	kg	4.43760E-4	1	1.12	(1,1,1,3,1,4); Eners 2005	21.189	2.629	76.182
	transport, lorry 28t	CH	0	tkm	4.99300E-5	1	2.09	(4,5,na,na,na,na); Standard distances 50 km	21.560	0.925	77.515
	transport, lorry 16t	CH	0	tkm	1.00000E-1	1	2.09	(4,5,na,na,na,na); Standard distances 100 km	12.018	44.773	43.209
	transport, freight, rail	CH	0	tkm	5.99160E-4	1	2.09	(4,5,na,na,na,na); Standard distances 600km	21.560	0.925	77.515
	electricity, medium voltage, at grid	CH	0	kWh	7.30413E-3	1	1.12	(1,1,1,3,1,4); Eners 2005	19.218	11.684	69.098
	heat, at cogen with gas engine, allocation exergy	CH	0	MJ	6.74764E-2	1	1.11	(1,1,1,1,1,4); Frometin 2000	21.524	1.088	77.388
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	1.23732E-1	1	1.12	(1,1,1,3,1,4); Eners 2005	21.524	1.088	77.388
	ethanol fermentation plant	CH	1	unit	1.07000E-11	1	3.09	(2,4,1,5,3,4); Estimation	12.018	44.773	43.209
emission air, high population density	Heat, waste	-	-	MJ	2.62947E-2	1	1.11	(1,1,1,1,1,4); Calculated from the electricity input	19.218	11.684	69.098
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	5.03365E-2	1	1.12	(1,1,1,3,1,4); Calculated from the carbon balance	-41.517	63.874	77.643
	BOD5, Biological Oxygen Demand	-	-	kg	7.88367E-4	1	1.56	(1,2,1,1,3,3); Calculated from the water emissions	12.018	44.773	43.209
	COD, Chemical Oxygen Demand	-	-	kg	7.88367E-4	1	1.56	(1,2,1,1,3,3); Calculated from the water emissions	12.018	44.773	43.209
	DOC, Dissolved Organic Carbon	-	-	kg	3.15347E-4	1	1.58	(3,na,na,3,1,5); Extrapolation for sum parameter	12.018	44.773	43.209
	TOC, Total Organic Carbon	-	-	kg	3.15347E-4	1	1.56	(1,2,1,1,3,3); Calculated from the water emissions	12.018	44.773	43.209

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	whey , to fermentation
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Fermentation of whey including materials, energy uses, infrastructure, and emissions.
	404	Amount	1
	490	LocalName	Molke, in Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput-process "whey, to fermentation" delivers the co-products Ethanol, 95% in H20, from whey", "yeast paste from whey", and "portein concentrate rom whey". The allocation is based on economic criteria. The production of ethanol from whey is of no economical importance in the world.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	production
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	The inventory is modelled with data from a plant in Ireland.
Technology	692	Text	Production of ethanol from whey with the Carbery process.
Representativene	722	Percent	0
	724	ProductionVolume	The world production of ethanol from whey was 6.8 Million litres per year.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

14.8 Cumulative Results and Interpretation

14.8.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific in-

puts from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

14.8.2 Ethanol 95% from biomass

Tab. 14.28 shows the selected LCI results and the cumulative energy demand for ethanol production from sugar beets.

Tab. 14.28 Selected LCI results and the cumulative energy demand for the production of ethanol from sugar beets

c		Name	Unit	ethanol, 95% in H2O, from sugar beets, at fermentation plant	beet chips, at fermentation plant
		Location		CH	CH
		Unit		kg	kg
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	8.2	0.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.4	0.2
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.6	0.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	28.7	4.9
LCI results					
resource	Land occupation	total	m2a	1.2E+0	2.1E-1
air	Carbon dioxide, fossil	total	kg	4.9E-1	4.2E-2
air	NMVOC	total	kg	4.6E-4	6.2E-5
air	Nitrogen oxides	total	kg	2.4E-3	3.7E-4
air	Sulphur dioxide	total	kg	1.1E-3	7.7E-5
air	Particulates, < 2.5 um	total	kg	2.3E-4	3.8E-5
water	BOD	total	kg	8.5E-4	1.3E-4
soil	Cadmium	total	kg	-5.1E-7	-8.7E-8
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-4.0E-1
air	Carbon dioxide, land transformation	low population density	kg	2.6E-5	7.4E-7
air	Methane, biogenic	total	kg	8.1E-6	2.2E-7
air	Carbon monoxide, biogenic	total	kg	1.0E-4	1.5E-5

Tab. 14.29 shows the selected LCI results and the cumulative energy demand for ethanol production from grass.

Tab. 14.29 Selected LCI results and the cumulative energy demand for the production of ethanol from grass

c		Name		ethanol, 95% in H2O, from grass, at fermentation plant	proteins from grass, at fermentation	grass fibres, at fermentation
		Location		CH	CH	CH
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	4.4	2.9	3.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	4.5	3.8	2.8
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.4	1.2	0.9
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	28.9	24.7	41.2
LCI results						
resource	Land occupation	total	m2a	1.5E+0	1.3E+0	2.1E+0
air	Carbon dioxide, fossil	total	kg	2.8E-1	1.9E-1	2.4E-1
air	NMVOC	total	kg	3.0E-4	2.3E-4	3.5E-4
air	Nitrogen oxides	total	kg	1.4E-3	1.1E-3	1.8E-3
air	Sulphur dioxide	total	kg	5.6E-4	3.4E-4	4.1E-4
air	Particulates, < 2.5 um	total	kg	1.3E-4	1.1E-4	1.6E-4
water	BOD	total	kg	5.1E-4	4.1E-4	6.4E-4
soil	Cadmium	total	kg	-1.3E-7	-1.1E-7	-1.9E-7
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-1.5E+0	-1.6E+0
air	Carbon dioxide, land transformation	low population density	kg	6.9E-7	4.9E-7	7.3E-7
air	Methane, biogenic	total	kg	1.5E-4	3.9E-5	3.3E-5
air	Carbon monoxide, biogenic	total	kg	3.2E-4	8.4E-5	7.7E-5

Tab. 14.30 shows the selected LCI results and the cumulative energy demand for ethanol production from whey.

Tab. 14.30 Selected LCI results and the cumulative energy demand for the production of ethanol from whey

c		Name		ethanol, 95% in H2O, from whey, at fermentation plant	protein concentrate, from whey, at fermentation	yeast paste, from whey, at fermentation
		Location		CH	CH	CH
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.5	2.1	17.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.7	0.2	2.3
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.2	0.1	0.7
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0	0.0	0.0
LCI results						
resource	Land occupation	total	m2a	6.0E-3	2.6E-3	1.9E-2
air	Carbon dioxide, fossil	total	kg	3.3E-1	1.3E-1	1.0E+0
air	NMVOC	total	kg	5.2E-4	3.0E-4	1.6E-3
air	Nitrogen oxides	total	kg	1.8E-3	1.1E-3	5.8E-3
air	Sulphur dioxide	total	kg	4.5E-4	1.6E-4	1.4E-3
air	Particulates, < 2.5 um	total	kg	1.2E-4	7.0E-5	3.7E-4
water	BOD	total	kg	6.1E-3	3.8E-3	1.9E-2
soil	Cadmium	total	kg	1.1E-9	6.9E-10	3.5E-9
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-1.4E-1	-2.9E-1
air	Carbon dioxide, land transformation	low population density	kg	6.1E-6	6.9E-7	1.9E-5
air	Methane, biogenic	total	kg	8.9E-6	2.4E-7	2.8E-5
air	Carbon monoxide, biogenic	total	kg	2.5E-5	4.4E-6	7.9E-5

Tab. 14.31 shows selected LCI results and the cumulative energy demand for the production of ethanol from grass, sugar beets, and whey.

There are great differences in the cumulative energy demand between the several resources. Relevant is the energy use during the ethanol conversion process. The differences are due to the diverse techniques with varying energy inputs and the different allocation factors because of the economic value of the co-products. The value for ethanol from whey for the CED renewable resources from biomass comes from the calculation of whey as a waste with no energy content.

Tab. 14.31 Selected LCI results and the cumulative energy demand for the production of ethanol from biomass

c		Name		ethanol, 95% in H2O, from whey, at fermentation plant	ethanol, 95% in H2O, from grass, at fermentation plant	ethanol, 95% in H2O, from sugar beets, at fermentation plant
		Location		CH	CH	CH
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.5	4.4	8.2
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.7	4.5	1.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.2	1.4	0.6
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0	28.9	28.7
LCI results						
resource	Land occupation	total	m2a	6.0E-3	1.5E+0	1.2E+0
air	Carbon dioxide, fossil	total	kg	3.3E-1	2.8E-1	4.9E-1
air	NMVOC	total	kg	5.2E-4	3.0E-4	4.6E-4
air	Nitrogen oxides	total	kg	1.8E-3	1.4E-3	2.4E-3
air	Sulphur dioxide	total	kg	4.5E-4	5.6E-4	1.1E-3
air	Particulates, < 2.5 um	total	kg	1.2E-4	1.3E-4	2.3E-4
water	BOD	total	kg	6.1E-3	5.1E-4	8.5E-4
soil	Cadmium	total	kg	1.1E-9	-1.3E-7	-5.1E-7
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-1.9E+0	-1.9E+0
air	Carbon dioxide, land transformation	low population density	kg	6.1E-6	6.9E-7	2.6E-5
air	Methane, biogenic	total	kg	8.9E-6	1.5E-4	8.1E-6
air	Carbon monoxide, biogenic	total	kg	2.5E-5	3.2E-4	1.0E-4

In Tab. 14.32 a comparison of energy balances (MJ energy input / MJ energy output) from several references is given for the ethanol production from sugar beets.

Tab. 14.32 Comparison of energy balances of the ethanol production from sugar beets

Source	Energy balance (MJ input/MJ output)
This study	1.37
GM 2002 (highest value)	2.57
GM 2002 (lowest value)	2.17
Novem 1992	1.3
ERL 1990 (quoted in Novem 1992)	1.07
CEC 1988 (quoted in Novem 1992)	1.81
ENEA 1988 (quoted in Novem 1992)	2.26

For the whey and grass routes there are no data available from other references, because this production routes are of no importance in the world ethanol production.

14.9 Ethanol, 99.7 % in H_2O from biomass, at distillation, CH

For fuel ethanol anhydrous ethanol (99.7 % m/m) is needed. It is not possible to remove remaining water from rectified spirit by straight distillation as ethanol forms a constant boiling mixture with water at a concentration of 95% m/m and is known as azeotrope. Therefore, a special process for removal of water is required for the production of absolute alcohol. The ethanol is dehydrated at the ethanol plant. Therefore no transports are considered.

Most ethanol plants use the molecular sieve technology or pervaporation for ethanol dehydration. For this report the molecular sieve separation is considered.

Process description (Galitsky 2003)

From feed tank, rectified spirit is pumped to the Stripper / Rectifier Column. A partial steam of vapours from the Column are condensed in Condenser and sent back to the column as reflux. Rest of the vapours are passed through a super-heater and taken to the Molecular Sieve units for dehydration. The vapour passes through a bed of molecular sieves. The water in the incoming vapour stream is adsorbed on the molecular sieve material and anhydrous ethanol vapour comes out from the Molecular Sieve Unit. The hot anhydrous ethanol vapour from the Molecular Sieve Units is condensed in the Molecular Sieve Condenser. The anhydrous ethanol product is cooled down in the product cooler to ambient temperature. The two Molecular Sieve units operate sequentially and are cycled so that one is under regeneration while the other is under operation adsorbing water from the vapour stream. The regeneration is accomplished by applying vacuum to the bed undergoing regeneration. The adsorbed material from the molecular sieves desorbs and evaporates into the ethanol vapour stream. This mixture of ethanol and water is condensed and cooled with cooling tower water as counter flow in the Molecular Sieves Regenerant Condenser. Any uncondensed vapour and entrained liquid leaving the Molecular Sieve Regenerant Condenser enters the Molecular Sieve Regenerant Drum, where it is contacted with cooled regenerant liquid. The remaining water is considered as waste water to river.

Ethanol mix

Most ethanol in the world is produced by sugar cane and corn (around 90 %). The production of ethanol from corn and sugar cane should be accounted because of their great importance in the world ethanol production, but so long there are no datasets for these processes available. In the year 2004 no ethanol, which was used as fuel, was produced in Switzerland at a commercial range. The potentials available in Switzerland for several production routes are given in Tab. 14.33. The data are taken from Fromentin 2000 and are based on the Swiss overproduction of these products. These potentials are taken to calculate an ethanol mix for Switzerland.

Tab. 14.33 Potentials for ethanol production in Switzerland and factors for the ethanol mix

Input	Ethanol production (l) 1	Mix factor 2
Ethanol from sugar beets	72000000	0.277
Ethanol from whey	16300000	0.063
Ethanol from grass	171600000	0.660

1 Source: Fromentin 2000

2 Factor for the ethanol mix for Switzerland

It is planned to build up an ethanol plant, which produces 45 Mio litres of ethanol per year as from 2007 (Alcosuisse 2003).

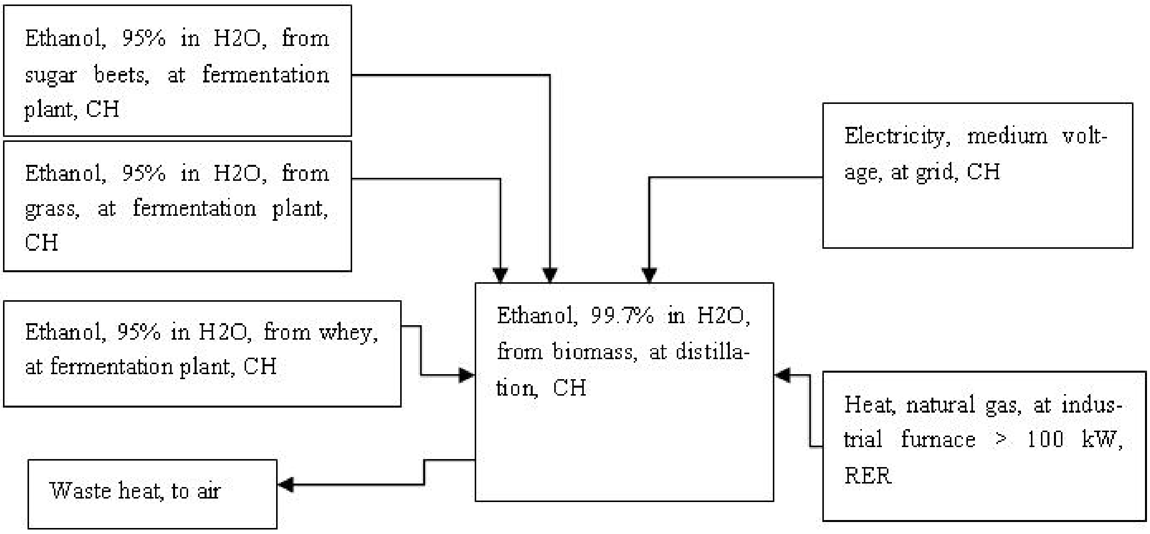

Fig. 14.7 Process flow chart for the production of ethanol, 99.7% in H2O, from biomass, at distillation, CH

It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

Tab. 14.34 shows the values for the inputs of "ethanol, 99.7% in H2O, from biomass, at distillation, CH". As ethanol input 1 kg ethanol 95% per kg ethanol 99.7% is considered, because all calculations are based on ethanol 100%. As in the LCA reports of the ethanol production the energy inputs for the ethanol distillation and the dewatering units are usually accumulated, only one reference (Galitsky 2003) has been considered for this study.

As the processes of fermentation and distillation are not separated in the plant no infrastructure is considered. It is included in the fermentation process.

Tab. 14.34 Ethanol, 99.7%, from biomass, at distillation, CH: Inputs per kg ethanol

Input	per kg ethanol	Remark
Ethanol, 95% in H2O, from sugar beets, at fermentation plant, CH (kg)	0.277	Proportion factor according to Fromentin 2000
Ethanol, 95% in H2O, from whey, at fermentation plant, CH (kg)	0.063	Proportion factor according to Fromentin 2000
Ethanol, 95% in H2O, from grass, at fermentation plant, CH (kg)	0.660	Proportion factor according to Fromentin 2000
Steam (MJ)	6.25E-02	according to Galitsky 2003
Electricity (kWh)	8.36E-05	according to Galitsky 2003
Waste heat (MJ)	3.01E-04	calculated from the electricity input

14.9.1 Life cycle inventory of the supply of ethanol, 99.7% in H2O, from biomass, at distillation and data quality considerations

Tab. 14.35 shows the data quality indicators for supply of ethanol, 99.7% in H2O, from biomass, at distillation. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.35: Unit process raw data for the supply of ethanol, 99.7% in H2O, from biomass, at distillation

	401	InputGroup	OutputGrou	Name	Location	InfrastructureProcess	Unit	ethanol, 99.7% in H2O, from biomass, at distillation	UncertaintyType	StandardDeviation95%	GeneralComment
	662			Location				CH			
	493			InfrastructureProcess				0			
	403			Unit				kg			
		-	0	ethanol, 99.7% in H2O, from biomass, at distillation	CH	0	kg	1.0000E+0			
technosphere		5	-	ethanol, 95% in H2O, from sugar beats, at fermentation plant	CH	0	kg	2.7700E-1	1	1.24	(4,3,1,1,1,4); Fromentin 2000
		5	-	ethanol, 95% in H2O, from whey, at fermentation plant	CH	0	kg	6.3000E-2	1	1.24	(4,3,1,1,1,4); Fromentin 2000
		5	-	ethanol, 95% in H2O, from grass, at fermentation plant	CH	0	kg	6.6000E-1	1	1.24	(4,3,1,1,1,4); Fromentin 2000
		5	-	electricity, medium voltage, at grid	CH	0	kWh	8.3600E-5	1	1.12	(1,1,1,3,1,4); Galitsky 2003
		5	-	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	6.2500E-2	1	1.12	(1,1,1,3,1,4); Galitsky 2003
emission air, high population density		-	4	Heat, waste	-	-	MJ	3.00960E-4	1	1.14	(2,4,1,3,1,3); Calculated from the electricity input

14.9.2 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 14.36 shows selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from biomass, at distillation.

Tab. 14.36 Selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from biomass, at distillation

c		Name Location Unit Infrastructure	Unit	ethanol, 99.7% in H2O, from biomass, at distillation CH kg 0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	27.0
LCI results				
resource	Land occupation	total	m2a	1.3E+0
air	Carbon dioxide, fossil	total	kg	3.4E-1
air	NMVOC	total	kg	3.6E-4
air	Nitrogen oxides	total	kg	1.7E-3
air	Sulphur dioxide	total	kg	7.0E-4
air	Particulates, < 2.5 um	total	kg	1.6E-4
water	BOD	total	kg	9.5E-4
soil	Cadmium	total	kg	-2.3E-7
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-1.9E+0
air	Carbon dioxide, land transformation	low population density	kg	8.1E-6
air	Methane, biogenic	total	kg	1.0E-4
air	Carbon monoxide, biogenic	total	kg	2.4E-4

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	ethanol, 99.7% in H2O, from biomass, at distillation
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Dewatering of ethanol 95% in H2O including ethanol mix Switzerland.
	404	Amount	1
	490	LocalName	Ethanol, 99.7% in H2O, aus Biomasse, ab Destillation
	491	Synonyms	Alkohol//alcohol dehydrated//algrain//Anhydrol//cologne spirit//cologne spirits (alcohol)//Denatured alcohol//Ethyl alcohol//Ethanol//ethanol 200 proof//Ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//
	492	GeneralComment	The inventory for "ethanol, 99.7% in H2O, from biomass, at distillation, CH" is modelled with ethanol production from sugar beets, whey and grass. The mix was assumed with the potentials of the Swiss ethanol production in the year 2007, which have been considered in literature.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	C2H6O
	501	StatisticalClassification	
	502	CASNumber	000064-17-5
TimePeriod	601	StartDate	2000
	602	EndDate	2007
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	The inventory is modelled for Switzerland.
Technology	692	Text	Dewatering of ethanol
Representativene	722	Percent	10
	724	ProductionVolume	World ethanol production was around 276 Mio hl in 2003.
	725	SamplingProcedure	Literature data.
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

14.10 Ethanol, 99.7 % in H_2O from biomass, at service station, CH

The transport of the ethanol to the service station is assumed as 100 km by train and 150 km by lorry 28t. The regional storage is assumed as 2.6E-10 units of “regional distribution, oil products, CH”. The handling at the filling station is assumed with standard factors according to the chapter ”General methodology”: 6.7E-03 kWh electricity, low voltage and 6.21E-04 MJ light fuel oil. All inputs are given in Fig. 14.8.

As emission 5E-04 kg ethanol to air per kg ethanol product is considered. This value is calculated with the standard factors from the chapter "General methodology". It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

All other inputs and outputs are estimated with data for fuel distribution.

A use of nitrogen as cover gas to avoid water uptake is not considered in this report.

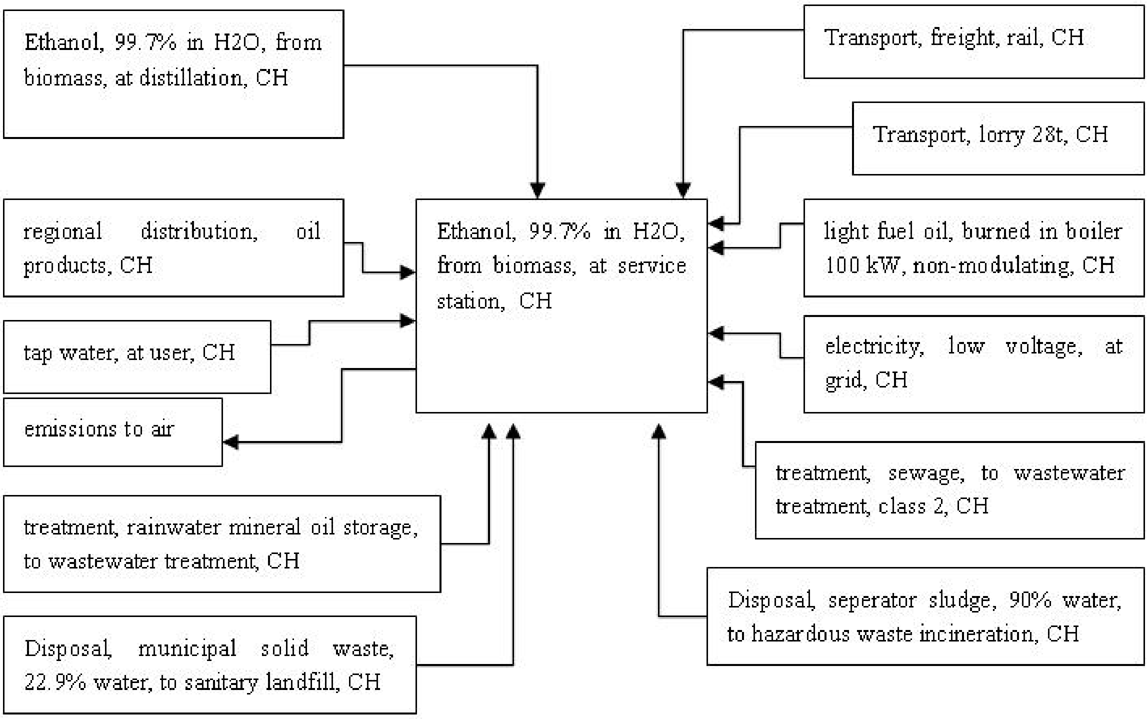

Fig. 14.8 Process flow chart for the production of ethanol from biomass, at service station fermentation, CH

Tab. 14.37 Ethanol, 99.7% in H2O, from biomass, at service station, CH: inputs

Input	per kg ethanol	Remark
Ethanol, 99.7% in H2O, from biomass, at distillation, CH (kg)	1.0005	Losses are estimated
Transport, lorry 28t, CH (tkm)	0.150527	Standard distance
Transport, train, CH (tkm)	0.100351	Standard distance
Electricity, low voltage, at grid, CH (kWh)	6.7E-03	Estimation
Light fuel oil, burned in boiler 100 kW, non-modulating, CH (MJ)	6.21E-04	Estimation
Tap water, at user, CH (kg)	6.89E-04	Estimation
Treatment, sewage, to wastewater treatment, class 2, CH (m3)	6.89E-07	Estimation
Treatment, rainwater mineral oil storage, to wastewater treatment, class 2	7.5E-05	Estimation
Disposal, municipal solid waste, 22.9% water, to sanitary landfill	6.27E-06	Estimation
Disposal, separator sludge, 90% water, to hazardous waste incineration	1.68E-04	Estimation
Regional distribution, oil products, CH (units)	2.6E-10	Estimation

Tab. 14.38 Ethanol, 99.7% in H2O, from biomass, at service station, CH: Outputs

Output	per kg ethanol	Remarks
Ethanol, to air, (kg)	5E-04	Estimation
Waste heat (MJ)	2.412E-02	calculated from the electricity input

14.10.1 Life cycle inventory of the supply of ethanol, 99.7% in H2O, from biomass, at service station and data quality considerations

Tab. 14.39 shows the data quality indicators for supply of ethanol, 99.7% in H2O, from biomass, at service station. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.39 Unit process raw data for the supply of ethanol, 99.7% in H2O, from biomass, at service station, CH

401	InputGroup	OutputGroup	Name	Location	InfrastructureProcess	Unit	ethanol, 99.7% in H2O, from biomass, at service station	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location				CH			
493			InfrastructureProcess				0			
403			Unit				kg			
	-	0	ethanol, 99.7% in H2O, from biomass, at service station	CH	0	kg	1.00000E+0			
technosphere	5	-	ethanol, 99.7% in H2O, from biomass, at distillation	CH	0	kg	1.00050E+0	1	1.05	(1,1,1,1,1,1); Product plus losses
	5	-	electricity, low voltage, at grid	CH	0	kWh	6.70000E-3	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21000E-4	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89000E-7	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50000E-5	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27000E-6	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68000E-4	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	5	-	tap water, at user	CH	0	kg	6.89000E-4	1	1.25	(2,4,1,3,3,3); Data for fuel distribution
	5	-	transport, freight, rail	CH	0	tkm	1.00351E-1	1	2.09	(4,5,na,na,na,na); Standard distances
	5	-	transport, lorry 28t	CH	0	tkm	1.50527E-1	1	2.09	(4,5,na,na,na,na); Standard distances
	5	-	regional distribution, oil products	RER	1	unit	2.60000E-10	1	3.09	(4,5,na,na,na,na); Estimation
emission air, high population density	-	4	Ethanol	-	-	kg	5.00000E-4	1	1.58	(3,na,1,3,3,na); Estimation
emission air, high population density	-	4	Heat, waste	-	-	MJ	2.41200E-2	1	1.14	(2,4,1,3,1,3); Calculated from the electricity input

14.10.2 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 14.40 shows selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from biomass, at service station.

Tab. 14.40 Selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from biomass, at service station

c		Name		ethanol, 99.7% in H2O, from biomass, at service station
		Location		CH
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	6.2
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.5
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	27.0
LCI results				
resource	Land occupation	total	m2a	1.3E+0
air	Carbon dioxide, fossil	total	kg	3.8E-1
air	NMVOC	total	kg	9.2E-4
air	Nitrogen oxides	total	kg	2.0E-3
air	Sulphur dioxide	total	kg	7.5E-4
air	Particulates, < 2.5 um	total	kg	1.7E-4
water	BOD	total	kg	1.1E-3
soil	Cadmium	total	kg	-2.3E-7
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-1.9E+0
air	Carbon dioxide, land transformation	low population density	kg	8.4E-6
air	Methane, biogenic	total	kg	1.0E-4
air	Carbon monoxide, biogenic	total	kg	2.4E-4

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	ethanol, 99.7% in H2O, from biomass, at service station
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformati	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Supply of ethanol at service stations in Swtzerland including ethanol production and transports.
	404	Amount	1
	490	LocalName	Ethanol, 99.7% in H2O, aus Biomasse, ab Tankstelle
	491	Synonyms	Alkohol//alcohol dehydrated//algrain//Anhydrol//cologne spirit//cologne spirits (alcohol)//Denatured alcohol//Ethyl alcohol//Ethanol//ethanol 200 proof//Ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//
	492	GeneralComment	The inventory for "ethanol, 99.7% in H2O, from biomass, at service station, CH" is modelled with data of the regional distribution of petrol in Switzerland.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	C2H6O
	501	StatisticalClassification	
	502	CASNumber	000064-17-5
TimePeriod	601	StartDate	2000
	602	EndDate	2005
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	The inventory is modelled for Switzerland with standard transport distances and standard distribution.
Technology	692	Text	Production of ethanol from biomass.
Representativene	722	Percent	10
	724	ProductionVolume	World ethanol production was around 276 Mio hl in 2003.
	725	SamplingProcedure	Literature data.
	726	Extrapolations	Transports are modelled with standard distances.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

14.11 Ethanol fermentation plant, CH

14.11.1 Process

The infrastructure of the ethanol plant was assessed using data from Central Illinois Energy 2002. In this publication a recently built ethanol plant with a production capacity of 90000 t ethanol per year was assessed. This plant size was used for this inventory. The lifetime of the plant is accounted with

20 years. Additional 5 years were accounted for construction and dismantling of the plant (Quincy Library Group 1997).

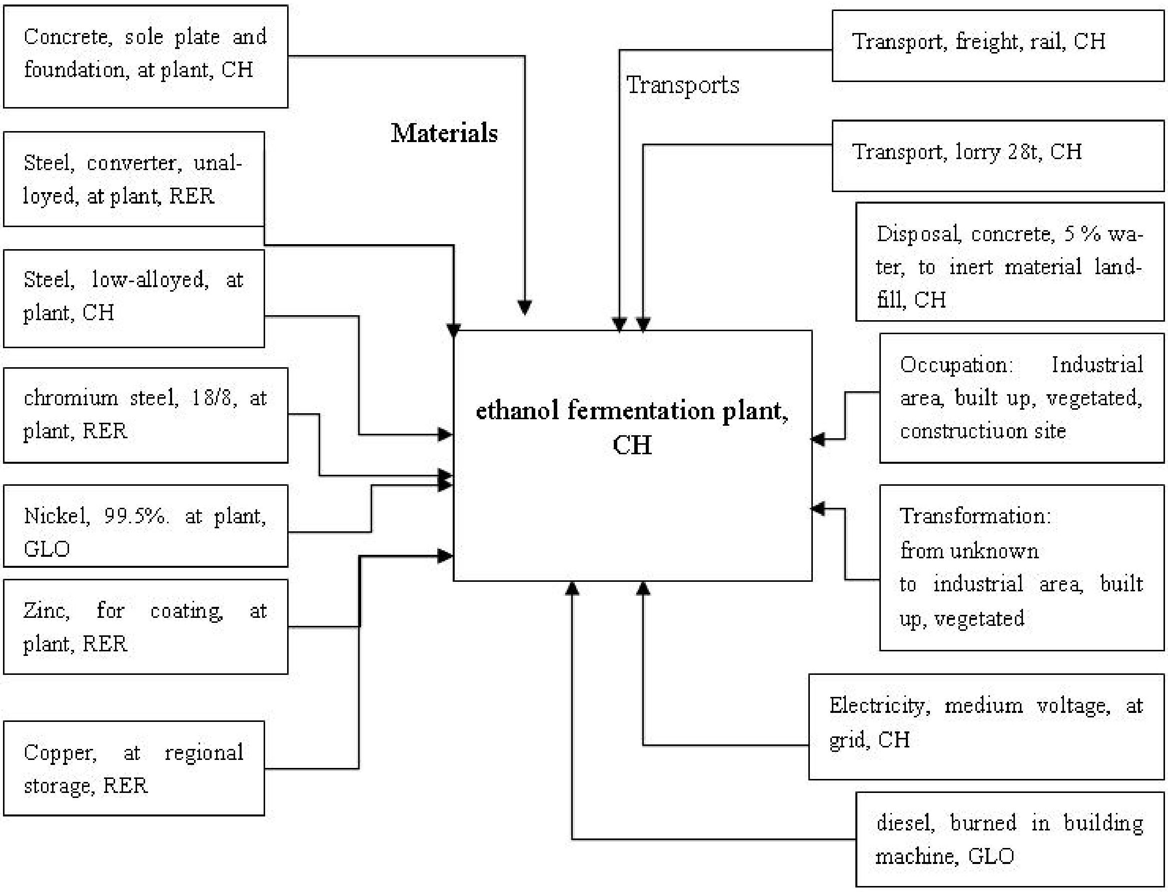

Fig. 14.9 Process flow chart for the ethanol plant infrastructure

14.11.2 Land use

The plant assessed in Hemstad 2005 occupies a land area of 0.009941 km^2. To receive a specific value (independent of the plant size) the land use was divided by the daily production capacity. This leads to a relative value of 0.152 m^2 d kg^{-1} or 0.0375 km^2 for the calculated ethanol plant. According to Hemstad 2005 it was assumed that only 0.096 m^2 d kg^{-1} or 0.023625 km^2 (63%) are built up area. The remaining area (0.056 m^2 d kg^{-1} or 0.013875 km^2) was accounted as "industrial area, vegetation". For the time of occupation, 20 years were assumed as plant life-time (production time). Further 5 years of occupation as construction site for construction and dismantling were used (QLG 1997). The occupation of the area before the occupation as industrial area is not known (transformation from unknown). Depending on the actual site conditions the occupation before the erection of the plant may be as industrial area, grassland or also as barren land. There was no information available and further investigated on that subject. The calculated values for the occupation and transformation of the whole site (plant with an ethanol production of 90000 t per year) and per kg of product used in this inventory are given in Tab. 14.41.

14.11.3 Infrastructure

Also for the infrastructure demand an ethanol plant with a production capacity of 90000 t ethanol per year was used. According to CIE 2002 the plant was built with 394.74 t unalloyed steel and 27300 t concrete (density 2200 kg/m^3). No information was readily available about the use of other materials and energy uses for the building machines. According to the dataset “methanol plant” in Althaus 2004 values for other materials were estimated (based on the unalloyed steel use): 167 t low alloyed steel, 145 t high alloyed steel, 86 t zinc, 36 t copper, and 3.2 t nickel. The values used in this inventory for the material demand of the plant (including reformer furnace) are given in Tab. 14.41. For the high-alloyed steel the process “chromium steel 18/8, at plant” was used. For the unalloyed steel the process “steel, converter, unalloyed, at plant” was used. To transport the materials to the plant, standard distances for Switzerland were applied (600 km rail, 50 km road for metals, 20 km road for concrete and 15 km road for the disposal of the concrete).

There are no data available on the energy demand needed for erecting and dismantling the plant. As an estimate, the values used in the dataset “building, multi story” were taken. The specific value for the energy used in building machines is 4.34 MJ kg-1 and for electricity use 1.86 MJ kg-1 (per kg plant weight). For the total weight of the plant an energy demand of 1,22*10^5 MJ as diesel in building machines and 5.32 *10^4 MJ as electricity is calculated. These values were used in the inventory.

14.11.4 Emissions to air

It is assumed, that 100% of the electricity consumed or 5.32*10^5 MJ is converted to waste heat. It is assumed that this waste heat is released to the air. Emissions from burning diesel in the building machines are considered within the dataset “diesel, burned in building machine”. Further emissions from erecting and dismantling the plant are not considered.

14.11.5 Waste processes

It is assumed that all metals are recycled and therefore no burden for disposal is included. For the concrete used in the plant the disposal process “disposal, building, concrete, not reinforced, to final disposal” is applied. There are no other wastes considered.

Tab. 14.41 Ethanol plant, inputs and outputs

Resource, Process	unit	per unit
Transformation, from unknown	m^2	3.75E+04
Transformation, to industrial area, built up	m^2	2.3625E+04
Transformation, to industrial area, vegetation	m^2	1.3875E+04
Occupation, construction site	m^2a	1.875E+05
Occupation, industrial area, built up	m^2a	4.725E+05
Occupation, industrial area, vegetation	m^2a	2.775E+05
concrete, sole plate and foundation, at plant	m^3	1.241E+04
steel, low-alloyed, at plant	kg	1.67E+05
steel, converter, unalloyed, at plant	kg	3.95E+05
chromium steel 18/8, at plant	kg	1.45E+05
zinc for coating, at regional storage	kg	8.60E+04
copper, at regional storage	kg	3.60E+04
nickel, 99.5%, at plant	kg	3.20E+03
transport, lorry 28t	tkm	9.98E+05
transport, freight, rail	tkm	4.99E+05
diesel, burned in building machine	MJ	1.22E+05
electricity, medium voltage, at grid	kWh	1.48E+04
disposal, building, concrete, not reinforced, to final disposal	kg	2.73E+07
Heat, waste	MJ	5.32008E+04

14.11.6 Life cycle inventory of an ethanol plant and data quality considerations

Tab. 14.42 shows the data quality indicators for the inventory of an ethanol plant. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 14.42 Unit process raw data of the construction of an ethanol plant

	3702	3703	3508	3706	3707	3708	3709	3792
	Name	Location	InfrastructureProcess	Unit	ethanol fermentation plant	UncertaintyType	StandardDeviation95	GeneralComment
	Location InfrastructureProcess Unit				CH 1 unit			
allocated	ethanol fermentation plant	CH	1	unit	1.00000E+0			
resources	Transformation, from unknown	-	-	m2	3.75000E+4	1	2.05	(1,1,1,3,1,5); Literature 2005
resources	Transformation, to industrial area, built up	-	-	m2	2.36250E+4	1	2.05	(1,1,1,3,1,5); Literature 2005
resources	Transformation, to industrial area, vegetation	-	-	m2	1.38750E+4	1	2.05	(1,1,1,3,1,5); Literature 2005
resources	Occupation, construction site	-	-	m2a	1.87500E+5	1	1.56	(1,1,1,3,1,5); Literature 2005
resources	Occupation, industrial area, built up	-	-	m2a	4.72500E+5	1	1.56	(1,1,1,3,1,5); Literature 2005
resources	Occupation, industrial area, vegetation	-	-	m2a	2.77500E+5	1	1.56	(1,1,1,3,1,5); Literature 2005
technosphere	concrete, sole plate and foundation, at plant	CH	0	m3	1.24091E+4	1	1.21	(1,1,1,3,1,5); Literature 2002
	steel, low-alloyed, at plant	RER	0	kg	1.67000E+5	1	1.30	(4,5,na,na,na,na); Estimation
	steel, converter, unalloyed, at plant	RER	0	kg	3.94700E+5	1	1.21	(1,1,1,3,1,5); Literature 2002
	chromium steel 18/8, at plant	RER	0	kg	1.45000E+5	1	1.30	(4,5,na,na,na,na); Estimation
	zinc for coating, at regional storage	RER	0	kg	8.60000E+4	1	1.30	(4,5,na,na,na,na); Estimation
	copper, at regional storage	RER	0	kg	3.60000E+4	1	1.30	(4,5,na,na,na,na); Estimation
	nickel, 99.5%, at plant	GLO	0	kg	3.20000E+3	1	1.30	(4,5,na,na,na,na); Estimation
	transport, lorry 28t	CH	0	tkm	9.97795E+5	1	2.09	(4,5,na,na,na,na); Standard distances
	transport, freight, rail	CH	0	tkm	4.99140E+5	1	2.09	(4,5,na,na,na,na); Standard distances
	diesel, burned in building machine	GLO	0	MJ	1.22000E+5	1	1.30	(4,5,na,na,na,na); Estimation
	electricity, medium voltage, at grid	CH	0	kWh	1.47780E+4	1	1.30	(4,5,na,na,na,na); Estimation
	disposal, building, concrete, not reinforced, to final disposal	CH	0	kg	2.73000E+7	1	1.30	(4,5,na,na,na,na); Estimation
emission air, high population density	Heat, waste	-	-	MJ	5.32008E+4	1	1.22	(1,2,1,1,3,3); Estimation from electricity input

14.11.7 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 14.43 shows selected LCI results and the cumulative energy demand for the construction of an ethanol plant.

Tab. 14.43 Selected LCI results and the cumulative energy demand for the construction of an ethanol plant

		Name		ethanol fermentation plant
c		Location		CH
		Unit	Unit	unit
		Infrastructure		1
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	47'658'000.0
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	9'185'000.0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4'303'600.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	154'650.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	505'960.0
LCI results				
resource	Land occupation	total	m2a	1.3E+6
air	Carbon dioxide, fossil	total	kg	4.2E+6
air	NMVOC	total	kg	3.1E+3
air	Nitrogen oxides	total	kg	1.6E+4
air	Sulphur dioxide	total	kg	1.7E+4
air	Particulates, < 2.5 um	total	kg	3.9E+3
water	BOD	total	kg	1.3E+4
soil	Cadmium	total	kg	4.6E-3
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	2.1E+4
air	Carbon dioxide, land transformation	low population density	kg	1.3E+1
air	Methane, biogenic	total	kg	1.1E+1
air	Carbon monoxide, biogenic	total	kg	9.5E+1

Appendix: EcoSpold Meta Information

Type	ID	**Field name, IndexNumber**	6368
ReferenceFuncti on	401	Name	ethanol fermentation plant
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	1
ReferenceFunctio	403	Unit	unit
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Ethanol plant infrastructure including transformation and occupation of land, materials, energy uses, emissions, and dismanteling
	404	Amount	1
	490	LocalName	Ethanolvergärungsanlage
	491	Synonyms	
	492	GeneralComment	Ethanol plant with an annual capacity of 90 000 tons ethanol and a life time of 20 years .
	494	InfrastructureIncluded	
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1997
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Literature
Geography	663	Text	The inventory is modelled with data from a plant in the USA.
Technology	692	Text	Ethanol fermentation plant with wheat as resource.
Representativene	722	Percent	0
	724	ProductionVolume	90000 tons per year
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

Abbreviations

AHF	Ammonia, hydrolysis and fermentation process
AHNF	Acid hydrolysis, neutralization and fermentation process
SHF	Steam, hydrolysis and fermentation process
SSF	Saccharification and simultanous fermentation process

References

Alcosuisse 2003	Alcosuisse: Bioethanol-Treibstoffe im Dienste der nachhaltigen Entwicklung: Fakten und Daten. Retrieved 09.05.2005 from http://www.eav.admin.ch/d/h_carb.htm
Alcosuisse 2004	Alcosuisse: Geschäftsbericht 2003 der Eidgenössischen Alkoholverwaltung (EAV). Bern 2004
Althaus 2004	Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Primas A. and Osses M. (2004) Life Cycle Inventories of Chemicals. Final report ecoinvent 2000 No. 8, Swiss Centre for Life Cycle Inventories, Duebendorf, CH
Berg 2001	Berg, Christoph: World ethanol production 2001. Retrieved 23.08.3004 from http://www.distill.com/world_ethanol_production.html
BIN 2004	Bioenergy information network. Bioenergy conversion factors. Retrieved 23.08.2004 from http://bioenergy.ornl.gov/papers/misc/energy_conv.html
CIE 2002	Central Illinois Energy Cooperative Economic Impact Analysis. Online-Version under www.centralillinoisenergy.com/ pdf/CIE%20econmic%20impact%2011-15-02.pdf
ENERS 2005	ENERS: Ethanol production. Personal communication from Arnaud Dauriat 2005
Frischknecht 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Fromentin 2000	Fromentin, A., Biollay, F., Dauriat, H., Luca.Porta, H., Marchand, J.-D., Sarlos, G.: Caractérisation de filières de production de bioéthanol dans le contexte helvétique. Sur mandat de l'Office fédéral de l'énergie, rapport final. Lausanne 2000
Galitsky 2003	Galitsky, C., Worrell, E., Ruth, M.: Energy efficiency improvement and cost saving opportunities for the corn wet milling industry. An Energy Star guide for energy and plant managers. Ernest Orlando Berkeley National Laboratory. University of California. Berkeley 2003
GM 2002	Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study". GM, LBST, bp, Exxon Mobil, Shell, Total Fina Elf 2002
Hardi 2003	Hardi, M.: Methodenentwicklung für nachhaltige Energie- und Emissionsminderungsstrategien auf der Grundlage von Lebenszyklusanalysen. Energiewirtschaft und Anwendungstechnik. München 2003, TU-München. Diss.
Hemstad 2005	Hemstad, G. Value added agrficulture. A look at an operating facility. FarmTech Proceedings 2005: 60-62. Online version under www.farmtechconference.com/ PDF/2005proceedings/Hemstad_FT05.pdf
Jungbluth 2003	Jungbluth, N. (2003): Erdöl. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (ed. Dones R.). Final report

	ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, CH
Kaltschmidt 1997	Kaltschmidt, M., Reinhardt, G.: Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung. Vieweg, Braunschweig/Wiesbaden 1997
Nemecek 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004) Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Novem 1992	The feasibility of biomass production in the Netherlands Energy Economy. Novem, Apelsdoorn (NL), 1992
Novem 2003	Zessen, E. van, Weismann, M., Bakker, R., Elbersen, Reith, J., Uil, H. den: Ligno Cellulosic Ethanol. A second opinion. Report 2Gave-03.11. Netherlands Agency for Energy and Environment. Utrecht 2003
Oettli 2004	Oettli, B., Bedniaguine, D., Dauriat, A., Gnansounou, E., Chételat, J., Hersener, J., Meier, U., Schleiss, K.: Potentiale zur energetischen Nutzung von Biomasse in der Schweiz. Bundesamt für Energie Bern 2004
QLG 1997	Quincy Library Group: Northeastern Californian ethanol manufacturing feasibility study. 1997. Online version under: http://www.qlg.org/pub/act_acp/ethanol/feasibility.htm
Savaiko 2004	Savaikon, Bernard: A promising future for ethanol. World Ethanol and Biofuels Report vol. 2, No. 17 2004
Stemme 2005	Stemme, K., Gerdes, B., Harms, A., Kamphues, J.: Beet-vinasse (condensed molasses solubles) as an ingredient in diets for cattles and pigs – nutrive value and limitations. In: Journal of Animal Physiology and Animal Nutrition 89 (2005): 179-183
Ullmann 2004	Kosaric, N., Duvnak, Z.: Ethanol, Chapter 1, 2, . In: Ullmann's Encyclopedia of Industrial Chemistry, Seventh Edition, 2004 Electronic Release (ed. Fiedler E., Grossmann G., Kersebohm D., Weiss G. and Witte C.). 7 th Electronic Release Edition. Wiley InterScience, New York, Online-Version under: http://www.mrw.interscience.wiley.com/ueic/articles/a09_587/
Wyman 1992	Wymanm C. E.: State of the art of ethanol production from cellulosic bio mass. In: Proceedings of Automotive Engineers: p. 771-778 1992

15 Ethanol 99.7% in H_2O from sugar cane

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15.1 Reserves and Resources

In Brazil around 2.6E08 tons of sugar cane are produced, 85 % in the region Centre South. The remaining 15 % are produced in the North in the states Pernambuco, Alaoas, Paraira, Rio Grande do Norte, and Bahia (UNICA 2004). The 35 hugest plants in the South of Brazil are processing nearly 25 % of the whole Brazilian production (Borreroa 2003). In 2005 there have been 365 sugar cane processing plants in Brazil (IDEA 2005).

Ethanol production in 2005/06 is forecasted at a record 16.6 million m3, made up of 8.37 million m3 of anhydrous and 8.27 million m3 of hydrous ethanol (Isosugar 2005).

83 % of the Brazilian ethanol is produced from sugar cane, 17 % is produced from molasses (Eners 2006), a co-product of sugar production. Details about the Brazilian production of ethanol from sugar cane molasses can be found in chapter 16.

It is expected, that the ethanol market is rising more and more and that the Brazilian production rises to 30 million m^3. (JornalCana 2005). In Santos (in the South of São Paulo) a separate terminal just for the export of ethanol has been built (Recco 2005).

Small plants are processing 70'000 t of sugar cane per year, huge plants can process up to 600000 t per year (Borreroa 2003). In the region Centre South the conversion is achieved from May to November (Granelli 2005). In the region North East the harvesting time is between March and September (UNICA 2004). Möllersten (2003) reports an average ethanol production of 500 m^3 per day.

15.2 System Characterisation

This report corresponds to the production of **ethanol 99.7% in H_2O from sugar cane, at service station, CH**. The following processes are modelled:

- sugar cane to fermentation, BR. Multioutput process with ethanol and electricity as allocated products
- ethanol, 95% in H_2O from sugar cane, at fermentation plant, BR
- electricity, bagasse, at fermentation plant, BR
- ethanol, 99.7% in H_2O from sugar cane, at distillation, BR
- ethanol, 99.7% in H_2O from sugar cane BR, at service station, CH

All data in the present report are referred to 1 kg ethanol 100%. The system includes the process with consumption of raw materials, energy, infrastructure and land use as well as the emissions to air and water. It also includes transportation of the raw materials. Transient or unstable operations like starting-up or shutting-down, are not included, but the only production during stable operation conditions. It is assumed that the manufacturing plants are located in an urban/industrial area and consequently the emissions are categorised as emanating in a high population density area. The emissions into water are assumed to be emitted into rivers.

15.3 Sugar cane to fermentation, BR

15.3.1 Production Technologies

The sugar cane is washed and then chipped into small pieces. These are pressed in several mills. At the mill, the cane is mechanically unloaded and placed in a large pile. The milling process occurs in two steps: breaking the hard structure of the cane and grinding the cane. Breaking the cane uses revolving knives, shredders, crushers, or a combination of these processes. For the grinding, or milling, of the crushed cane, multiple sets of three-roller mills are most commonly used although some mills consist of four, five, or six rollers in multiple sets. Conveyors transport the crushed cane from one mill to the next. Imbibition is the process in which water or juice is applied to the crushed cane to enhance the extraction of the juice at the next mill. In imbibition, water or juice from other processing areas is introduced into the last mill and transferred from mill to mill towards the first two mills while the crushed cane travels from the first to the last mill. The crushed cane exiting the last mill is called bagasse.

The sugar containing juice is caught, then sterilized and shifted with yeast, so that the sugar is converted in relatively short time (hours up to few days) to ethanol (Dinkel 1998).

In the fermentation the following simple chemical reaction happens:

$C_{12}H_{22}O_{11} + H_2O \rightarrow 4\ C_2H_5OH + 4\ CO_2$

In a distillation unit the ethanol is concentrated up to 95 % v/v with stillage as a by-product. The stillage is used as fertilizer in the sugar cane cultivation. The ligneous parts of the sugar cane remain as bagasse, which is used for producing steam used in the ethanol plant.

15.3.2 Raw materials and auxiliaries

Tab. 15.1 Raw materials, auxiliaries, and products of the ethanol production from sugar cane

		per kg sugar cane
Input	Water [3] [kg]	1.04
	Sulphuric acid [4] [kg]	7.24E-04
	Lubricants[4] [kg]	1.34E-05
	Limestone[4] [kg]	9.32E-04
Output	Ethanol [1] [kg]	6.68E-02
	Electricity [2] [kWh]	5.86E-03

1 Source: Borreroa 2003

2 Source: Tuchschmid 2006

3 Source: CETESB 1988

4 Source: Macedo 2004

Macedo (1996) report a substantial increase of the conversion yields. In 1985 the ethanol yield per ton sugar cane was around 73 l, in 1995 around 87.5 l. This increase is caused by the optimization of all production parameters (Moreira 1999). The Copersucar association report 84.5 l per ton sugar cane (Borreroa 2003). This value is used for this study.

Water

In the plants in the state São Paulo water is normally taken from damed rivers (Tuchschmid 2005). Because water is no scarce resource in the state São Paulo there are only few water saving measures (Tuchschmid 2005).

Percebon 1985 reports that 32 - 125 l water are used per l ethanol. The water is changed tertian (Granelli 2005). In a new plant in São Martinho / Pradópolis the stillage is cleaned (Marcello 2005). The nutrious filtrate can be used as fertilizer (Anselmi 2005).

CETESB 1988 reports a water use of 0.97 m3 per ton sugar cane (12.2 l water per l ethanol). This value is used for this study (Tuchschmid 2005).

Auxiliaries

Before fermentation sulphuric acid is added to the juice. 9.04 g per l ethanol are used (Macedo 2004).

For the yeast, which is used for the fermentation, small quantities of antibiotics are needed to avoid infectations (Granelli 2005, Bichara 1990). As no data are available for the production of yeasts and antibiotica these auxilliaries are neglected in this study.

Other auxiliaries, which are needed in the ethanol production from sugar cane, are lubricants and limestone.

15.3.3 Energy and burning of bagasse

The energy, which is used for the ethanol plant, is produced in the plants by burning the bagasse. Per t sugar cane an amount of 250 kg bagasse is generated. (Bichara 1990). 5 kg steam is produced from 1 kg bagasse (Filho 1984 , quoted in Bichara 1990). That means that 1250 kg steam is produced per t sugar cane. For the production of ethanol from 1 t sugar cane 500 kg steam is needed (Macedo 2004). The remaining steam is used to generate electricity, which is sold. 5.86 kWh electricity is produced per t sugar cane. (Macedo 2004). It is expected, that the generation of electricity is becoming more and more important for the ethanol plants (UNICA 2004, Freire 2005, Anselmi 2005, Mathias 2005).

Tab. 15.2 Energy output from the ethanol production from sugar cane (Macedo 2004)

Output	per kg sugar cane
Electricity (kWh)[1]	5.86E-03

The burning of bagasse is calculated with the dataset “wood chips, burned in cogen 6400kWth”. This process is adapted according to the following rules:

- all inputs from the technosphere are considered to be proportional to the dry matter input;
- emissions of hydrocarbons are proportional to the carbon input
- emissions of heat waste are proportional to the energy input
- all other emissions are proportional to the dry matter input

The properties of unconverted solids are given in Tab. 15.3 and compared with wood chips (u=40%).

Tab. 15.3 Characteristics and properties of pressed sugarcane bagasse, compared with wood chips (u=40%).

Output	Sugar cane bagasse	Wood chips, u=40%
Water content	50 % w/w	28.6 % w/w
Dry matter	50 % w/w	71.4 % w/w
Carbon content (dry matter basis)	44.3 % w/w	49.4 % w/w
Higher heating value	19.6 MJ/kg	20.2 MJ/kg
Lower heating value	9.8 MJ/kg	14.4 MJ/kg
Dry matter input	0.5 kg/kg	0.714 kg/kg
Carbon input	0.222 kg/kg	0.353 kg/kg
Energy input	5.83 MJ/kg	14.4 MJ/kg

Tab. 15.4 Inputs and outputs for the burning of bagasse from the fermentation of 1 kg sugar cane

	Elementary Flow	**per kg sugar cane**
Inputs	ammonia, liquid, at regional storehouse	1.50E-08
	chlorine, liquid, production mix, at plant	5.99E-07
	sodium chloride, powder, at plant	7.49E-06
	chemicals organic, at plant	1.05E-05
	lubricating oil, at plant	5.99E-06
	disposal, used mineral oil, 10% water, to hazardous waste incineration	5.99E-06
	disposal, wood ash mixture, pure, 0% water, to landfarming	2.41E-04
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	2.41E-04
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	4.84E-04
	disposal, municipal solid waste, 22.9% water, to municipal incineration	5.99E-06
	treatment, sewage, to wastewater treatment, class 2	1.44E-06
	water, decarbonised, at plant	1.44E-03
	cogen unit 6400kWth, wood burning, building	4.40E-10
	cogen unit 6400kWth, wood burning, common components for heat+electricity	1.76E-09
	cogen unit 6400kWth, wood burning, components for electricity only	1.76E-09
Outputs	Acetaldehyde	1.11E-07
	Ammonia	3.18E-06
	Arsenic	1.83E-09
	Benzene	1.66E-06
	Benzene, ethyl-	5.48E-08
	Benzene, hexachloro-	1.32E-14
	Benzo(a)pyrene	9.14E-10
	Bromine	1.10E-07
	Cadmium	1.28E-09
	Calcium	1.07E-05
	Carbon dioxide, biogenic	2.03E-01
	Carbon monoxide, biogenic	1.15E-05
	Chlorine	3.29E-07
	Chromium	7.24E-09
	Chromium VI	7.31E-11
	Copper	4.02E-08
	Dinitrogen monoxide	4.20E-06
	Dioxins	5.66E-14
	Fluorine	9.14E-08
	Formaldehyde	2.38E-07
	Heat, waste	1.75E+00
	Hydrocarbons, aliphatic, alkanes, unspecified	1.49E-06
	Hydrocarbons, aliphatic, unsaturated	5.08E-06
	Lead	4.55E-08
	Magnesium	6.60E-07
	Manganese	3.12E-07
	Mercury	5.48E-10
	Methane, biogenic	7.93E-07
	m-Xylene	2.19E-07
	Nickel	1.10E-08
	Nitrogen oxides	1.61E-04
	NMVOC, non-methane volatile organic compounds, unspecified origin	1.00E-06
	PAH, polycyclic aromatic hydrocarbons	1.80E-08

	Elementary Flow	**per kg sugar cane**
	Particulates, < 2.5 um	8.21E-05
	Phenol, pentachloro-	1.48E-11
	Phosphorus	5.48E-07
	Potassium	4.28E-05
	Sodium	2.38E-06
	Sulfur dioxide	4.55E-06
	Toluene	5.48E-07
	Zinc	5.48E-07

15.3.4 Transportation

For the transport of the sugar cane to the ethanol plant an average distance of 16 km is calculated (Macedo 1996). Three different types of lorries are taken into account (Macedo 1996): lorry 16 t (10 % of the sugar cane), lorry 32 t (50 %), and lorry 40 t (40 %).

No information is available in the sources consulted concerning transportation of the auxiliaries. Therefore, the following standard distances as defined in Frischknecht et al. (2003) for Europe are used: 100 km by lorry 32t and 600 km by train.

Tab. 15.5 Total transport services required for the production of ethanol from sugar cane

	tkm kg^{-1} sugar cane
lorry 16 t	1.6E-03
lorry 32 t	8.17E-03
lorry 40 t	6.4E-03
rail	1.03E-03

15.3.5 Infrastructure and land use

The infrastructure is estimated based on the dataset "ethanol fermentation plant, CH". This dataset assumes a built area of about 3.75 ha, an average output of 90'000 t/a, and a plant life of twenty years. The estimated value is 4.44 E-11 units per kg of sugar cane fermented.

15.3.6 CO2-uptake

The C-content of the stillage is calculated as an uptake of biogenic CO_2 from the air.

Tab. 15.6 Uptake of CO2

Input	per kg sugar cane	Remarks
Carbon dioxide, resource, in air	2.29E-02	According to the C-content of the stillage

15.3.7 Emissions to air

During the fermentation CO_2 is produced as an emission to air (Möllersten 2003). The amount of this emission is calculated from the carbon balance:

Carbon content sugar cane – Carbon content – emissions from bagasse burning.

The emissions from bagasse burning are described in chapter 15.3.3.

Tab. 15.7 Process emissions to air from the fermentation of 1 kg sugar cane

Output	per kg sugar cane	Remarks
Carbon dioxide, biogenic, to air (kg)	3.15E-01	Calculated from the carbon balance

15.3.8 Wastewater

The wastewater from the washing and other processes and the stillage from the distillation unit are used as fertilizer in the sugar cane cultivation (de Reynier 2005, Granelli 2005). In this study these wastewaters are calculated as “vinasse from sugar cane”. CETESB 1988 reports a value of 10 l stillage per l ethanol, Hassuda 1989 reports 12 l stillage, and Bichara 1990 13 l. The vinasse contains organic matter, phosphorus, nitrogen, and potassium. (Borreroa 2003). The COD is estimated around 15 to 35 g/l (Bichara 1990). In Tab. 15.9 the composition of stillage is given.

Tab. 15.8 Waste water from the ethanol production from sugar cane (Bichara 1990)

Output	per kg sugar cane	per kg ethanol
vinasse	1.1	16.5

Tab. 15.9 Properties of the vinasse from sugar cane processing (Bichara 1990)

Chemical Properties	Rodella 1980	Vasconcelos 1981	Average (this study)
N [g/l]	0.28	0.26	0.27
P2O5 [g/l]	0.09	0.49	0.29
K2O [g/l]	1.29	1.72	1.22
C [g/l]	6.7	7.58	7.14
Fe [ppm]	-	51.22	51.22
pH	3.7	3.57	3.635

15.3.9 Co-products and Allocation

Ash

Around 2.5 % of the burned bagasse remains as ash (6 kg per t sugar cane or 0.0949 kg per kg ethanol). The ash is used as fertilizer. No environmental impacts nor elementary flows are allocated to this byproduct. The composition of the ash is given in Tab. 15.10.

Tab. 15.10 Composition of the ash from bagasse burning (Bichara 1990)

Content	%
P2O5	0,87
K2O	1,67
CaO	0,99
MgO	0,56
Fe2O3	2,24
Al2O3	5,81
MnO	2,64
SiO2	85,22

Electricity from bagasse

The bagasse is used to generate energy (Bichara 1990, Granelli 2005). The surplus electricity is sold.

Tab. 15.11 Possible allocation parameters of the co-products from the ethanol production from sugar cane

Co-products	per kg sugar cane	Energy (MJ/kg sugar cane)	Economic value (R$/kg sugar cane)	Economic allocation factor (%)
Electricity	5.86E-03 kWh	2.11E-02	1.172E-04[3]	0.55
Ethanol	0.0668 kg	1.88	4.704E-02[3]	99.45

Sources:

1: CDM 2005

2: Fernandes 2005

3: Tuchschmid 2006

The price forms the basis of allocation of ethanol and electricity. The carbon contained in the stillage is allocated to the ethanol and the electricity.

Tab. 15.12 Allocation factors for the co-products of the ethanol production from sugar beets

Inputs/Outputs	Ethanol	Electricity	Stillage
Sugar cane	99.45	0.55	0
CO2, resource, in air	0	0	100
Water	99.45	0.55	0
Auxilliaries	99.45	0.55	0
Transports	99.45	0.55	0
Infrastructure	99.45	0.55	0
Inputs for bagasse burning	99.45	0.55	0
Emissions from bagasse burning	99.45	0.55	0
Waste heat	99.45	0.55	0
CO2, biogenic, to air	99.23	0.77	0

15.3.10 Life cycle inventory of the production of ethanol from sugar cane and data quality considerations

Tab. 15.13 shows the life cycle inventory and the data quality indicators of the production of ethanol from sugar cane. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 15.13 Unit process raw data for the production of ethanol from sugar cane

	Name	Location	Infrastructure Process	Unit	sugarcane, in fermentation	UncertaintyType	StandardDeviation95%	GeneralComment	ethanol, 95% in H2O, from sugar cane, at fermentation plant	electricity, bagasse, sugarcane, at fermentation plant	vinasse, from sugarcane, at fermentation
	Location				BR				BR	BR	BR
	InfrastructureProcess				0				0	0	0
	Unit				kg				kg	kWh	kg
allocated	ethanol, 95% in H2O, from sugar cane, at fermentation plant	BR	0	kg	6.68E-2				100.000	-	-
products	electricity, bagasse, sugarcane, at fermentation plant	BR	0	kWh	5.86E-3				-	100.000	-
	vinasse, from sugarcane, at fermentation	BR	0	kg	1.10E+0				-	-	100.000
resource, in air	Carbon dioxide, in air	-	-	kg	2.88E-2	1	1.12	(1,3,1,1,1,4); calculated from the carbon content	-	-	100.00
resource, in water	Water, river	-	-	m3	1.04E-3	1	1.12	(1,3,1,1,1,4); Literature 1998	99.45	0.55	-
technosphere	sugar cane, at farm	BR	0	kg	1.00E+0	1	1.12	(1,3,1,1,1,4); Literature 2003	99.45	0.55	-
	lubricating oil, at plant	RER	0	kg	1.34E-5	1	1.12	(1,3,1,1,1,4); Literature 2004	99.45	0.55	-
	sulphuric acid, liquid, at plant	RER	0	kg	7.24E-4	1	1.12	(1,3,1,1,1,4); Literature 2004	99.45	0.55	-
	lime, hydrated, packed, at plant	CH	0	kg	2.39E-3	1	1.12	(1,3,1,1,1,4); Literature 2004	99.45	0.55	-
	transport, lorry 16t	RER	0	tkm	8.17E-3	1	2.09	(4,5,na,na,na,na); Standard distances	99.45	0.55	-
	transport, lorry 32t	RER	0	tkm	6.40E-3	1	2.09	(4,5,na,na,na,na); Standard distances	99.45	0.55	-
	transport, lorry 40t	CH	0	tkm	1.00E-3	1	2.09	(4,5,na,na,na,na); Standard distances	99.45	0.55	-
	transport, freight, rail	RER	0	tkm	1.03E-3	1	2.09	(4,5,na,na,na,na); Standard distances	99.45	0.55	-
	disposal, wood ash mixture, pure, 0% water, to landfarming	CH	0	kg	3.36E-5	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	3.36E-5	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	6.72E-5	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	furnace, wood chips, hardwood, 1000kW	CH	1	unit	1.55E-9	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	ethanol fermentation plant	CH	1	unit	4.44E-11	1	3.09	(2,4,1,5,3,4); Estimation	99.45	0.55	-
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.15E-1	1	1.24	(4,3,1,1,1,4); Calculated from the carbon balance	99.23	0.77	-
	Acetaldehyde	-	-	kg	1.68E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Ammonia	-	-	kg	4.77E-7	1	2.12	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Arsenic	-	-	kg	2.76E-10	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Benzene	-	-	kg	2.25E-7	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Benzene, ethyl-	-	-	kg	7.42E-9	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Benzene, hexachloro-	-	-	kg	1.78E-15	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Benzo(a)pyrene	-	-	kg	1.38E-10	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Bromine	-	-	kg	1.65E-8	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Cadmium	-	-	kg	1.93E-10	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Calcium	-	-	kg	1.61E-6	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Carbon dioxide, biogenic	-	-	kg	3.06E-2	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Carbon monoxide, biogenic	-	-	kg	1.01E-5	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Chlorine	-	-	kg	4.96E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Chromium	-	-	kg	1.09E-9	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Chromium VI	-	-	kg	1.10E-11	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Copper	-	-	kg	6.06E-9	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Dinitrogen monoxide	-	-	kg	6.34E-7	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	8.54E-15	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Fluorine	-	-	kg	1.38E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Formaldehyde	-	-	kg	3.58E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Heat, waste	-	-	MJ	2.89E-1	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	2.25E-7	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	7.66E-7	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Lead	-	-	kg	6.89E-9	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Magnesium	-	-	kg	9.92E-8	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Manganese	-	-	kg	4.68E-8	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Mercury	-	-	kg	8.27E-11	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Methane, biogenic	-	-	kg	9.89E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	m-Xylene	-	-	kg	3.31E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Nickel	-	-	kg	1.65E-9	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Nitrogen oxides	-	-	kg	2.87E-5	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.48E-7	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	2.74E-9	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Particulates, < 2.5 um	-	-	kg	1.68E-5	1	3.74	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Phenol	-	-	kg	2.23E-12	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Phosphorus	-	-	kg	8.27E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Potassium	-	-	kg	6.45E-6	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Sodium	-	-	kg	3.58E-7	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Sulfur dioxide	-	-	kg	6.89E-7	1	2.08	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Toluene	-	-	kg	8.27E-8	1	2.31	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-
	Zinc	-	-	kg	8.27E-8	1	5.86	(4,3,3,3,5,4); From bagasse burning	99.45	0.55	-

15.3.11 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 15.14 shows selected LCI results and the cumulative energy demand for the production of ethanol from sugar cane.

Tab. 15.14 Selected LCI results and the cumulative energy demand for the fermentation of sugar cane

		Name		ethanol, 95% in H2O, from sugar cane, at fermentation plant	electricity, bagasse, sugarcane, at fermentation plant	vinasse, from sugarcane, at fermentation
c		Location		BR	BR	BR
		Unit	Unit	kg	kWh	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.4	0.2	-
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.4	0.0	-
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.0	-
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	-
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	73.8	4.7	-
LCI results						
resource	Land occupation	total	m2a	2.0E+0	1.3E-1	0
air	Carbon dioxide, fossil	total	kg	2.1E-1	1.3E-2	0
air	NMVOC	total	kg	4.4E-4	2.8E-5	0
air	Nitrogen oxides	total	kg	3.6E-3	2.2E-4	0
air	Sulphur dioxide	total	kg	8.8E-4	5.6E-5	0
air	Particulates, < 2.5 um	total	kg	1.3E-3	8.5E-5	0
water	BOD	total	kg	6.7E-4	4.2E-5	0
soil	Cadmium	total	kg	4.7E-7	3.0E-8	0
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-2.6E+0	-4.5E-2	-2.6E-2
air	Carbon dioxide, land transformation	low population density	kg	2.8E-5	1.8E-6	0
air	Methane, biogenic	total	kg	4.3E-3	2.7E-4	0
air	Carbon monoxide, biogenic	total	kg	4.5E-1	2.8E-2	0

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	sugarcane, in fermentation
Geography	662	Location	BR
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	kg
DataSetInformation	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Fermentation of sugar cane including materials, energy uses, infrastructure, and emissions.
	404	Amount	1
	490	LocalName	Zuckerrohr, in Vergärung
	491	Synonyms	
	492	GeneralComment	The multioutput-process "sugar cane, to fermentation" delivers the co-products Ethanol, 95% in H20, from sugar cane" and "electricity, bagasse, at fermentation plant". The allocation is based on economic criteria.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	2000
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled for Brazil.
Technology	692	Text	Production of ethanol from sugar cane with extraction, fermentation, and distillation of ethanol. Capacity of the plant: 90000 t/a.
Representativeness	722	Percent	100
	724	ProductionVolume	Total production of ethanol from cane in Brazil is around 16.6 Mio m3 per a.
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAndPublication	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

15.4 Ethanol, 99.7 % in H_2O from sugar cane, at distillation, BR

15.4.1 Dehydration of the ethanol

For fuel ethanol anhydrous ethanol (99.7 % m/m) is needed. About half of the total ethanol production in Brazil is dehydrated (8.37 million m3 of 16.6 million m3, Isosugar 2005). It is not possible to remove remaining water from rectified spirit by straight distillation as ethanol forms a constant boiling mixture with water at a concentration of 95% m/m and is known as azeotrope. Therefore, a special process for removal of water is required for the production of absolute alcohol. The ethanol is dehydrated at the ethanol plant. Therefore no transports and infrastructures are considered.

83 % of the Brazilan ethanol is produced from sugar cane, 17 % is produced from molasse (Eners 2006), a co-product of sugar production.

Most ethanol plants use the molecular sieve technology or pervaporation for ethanol dehydration. The life cycle inventory is based on the molecular sieve separation.

Process description (Galitsky 2003)

From feed tank, rectified spirit is pumped to the Stripper / Rectifier Column. A partial steam of vapours from the Column are condensed in Condenser and sent back to the column as reflux. Rest of the vapours are passed through a super-heater and taken to the Molecular Sieve units for dehydration. The vapour passes through a bed of molecular sieves. The water in the incoming vapour stream is adsorbed on the molecular sieve material and anhydrous ethanol vapour comes out from the Molecular Sieve Unit. The hot anhydrous ethanol vapour from the Molecular Sieve Units is condensed in the Molecular Sieve Condenser. The anhydrous ethanol product is cooled down in the Product Cooler to ambient temperature. The two Molecular Sieve units operate sequentially and are cycled so that one is under regeneration while the other is under operation adsorbing water from the vapour stream. The regeneration is accomplished by applying vacuum to the bed undergoing regeneration. The adsorbed material from the molecular sieves desorbs and evaporates into the ethanol vapour stream. This mixture of ethanol and water is condensed and cooled with cooling tower water as counter flow in the Molecular Sieves Regenerant Condenser. Any uncondensed vapour and entrained liquid leaving the Molecular Sieve Regenerant Condenser enters the Molecular Sieve Regenerant Drum, where it is contacted with cooled regenerant liquid. The remaining water from the distillation is applied to the sugar cane fields together with the stillage and the waste waters from other processes of the ethanol production (Granelli 2005). Because these processes are not separated in the ethanol plant no stillage production is considered. It is included in the fermentation process.

It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

As ethanol input 1 kg ethanol 95% per kg ethanol 99.7% is considered (all values are based on ethanol 100%). As in the LCA reports of the ethanol production the energy inputs to the ethanol distillation and the dewatering units are usually aggregated, only one reference (Galitsky 2003) has been considered for this study.

As the processes of fermentation and distillation are not separated in the plant no infrastructure is considered. It is included in the fermentation process.

As total excess steam is considered to be sold as electricity no process "steam from bagasse" is modelled. The environmental impacts of the dataset "electricity from bagasse" are the same because these processes are not separated in the ethanol plant.

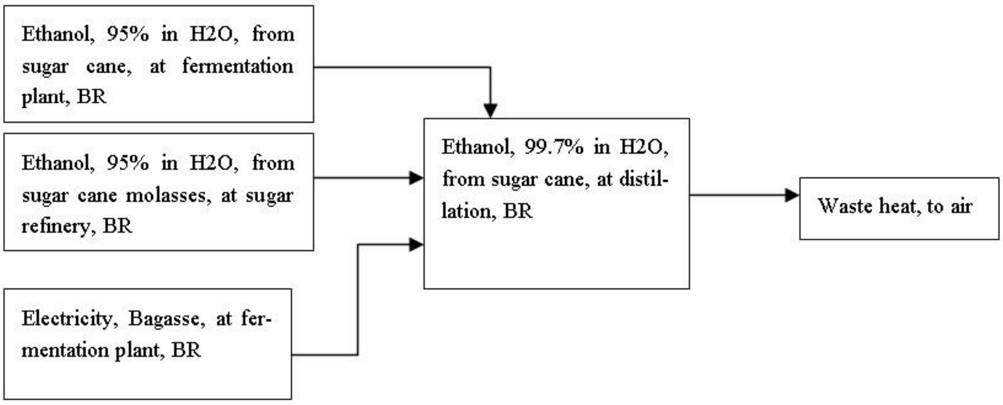


Fig. 15.1 Process flow chart of the production of ethanol, 99.7% in H2O, from biomass, at distillation, CH

Tab. 15.15 Energy inputs and waste heat output of the dehydration of ethanol

Input	per kg ethanol	Remark
Electricity (kWh)	1.74E-02	according to Galitsky 2003 and Macedo 2004
Waste heat (MJ)	6.28E-02	calculated from the electricity input

15.4.2 Life cycle inventory of the supply of ethanol, 99.7% at distillation and data quality considerations

Tab. 15.16 shows the life cycle inventory and the data quality indicators of the supply of ethanol, 99.7% in H2O, from biomass, at distillation. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 15.16 Unit process raw data for the supply of ethanol, 99.7% in H2O, from sugar cane, at distillation

401	InputGroup	OutputGrou	Name	Location	InfrastructureProcess	Unit	ethanol, 99.7% in H2O, from biomass, at distillation	UncertaintyType	StandardDeviation95%	GeneralComment
662			Location				BR			
493			InfrastructureProcess				0			
403			Unit				kg			
	-	0	ethanol, 99.7% in H2O, from biomass, at distillation	BR	0	kg	1.0000E+0			
technosphere	5	-	ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery	BR	0	kg	1.7000E-1	1	1.24	(4,3,1,1,1,4); Eners 2006
	5	-	ethanol, 95% in H2O, from sugar cane, at fermentation plant	BR	0	kg	8.3000E-1	1	1.24	(4,3,1,1,1,4); Eners 2006
	5	-	electricity, bagasse, sugarcane, at fermentation plant	BR	0	kWh	8.3600E-5	1	1.12	(1,1,1,3,1,4); Galitsky 2003
emission air, high population density	-	4	Heat, waste	-	-	MJ	3.00960E-4	1	1.14	(2,4,1,3,1,3); Calculated from the electricity input

15.4.3 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 15.17 shows selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from sugar cane, at distillation.

Tab. 15.17 Selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from sugar cane BR, at distillation

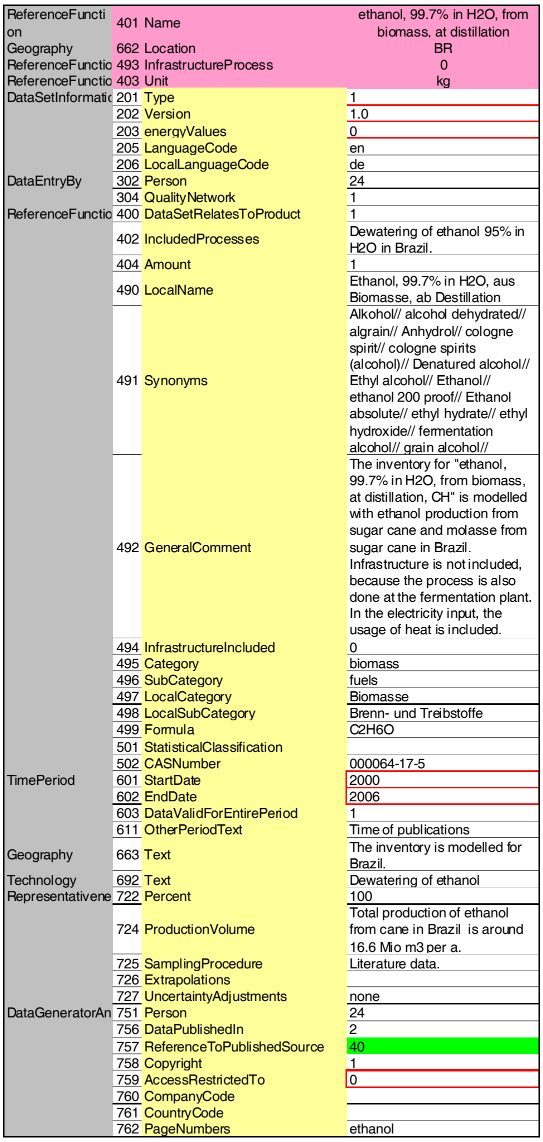
		Name		ethanol, 99.7% in H2O, from biomass, at distillation
c				
		Location		BR
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	71.3
LCI results				
resource	Land occupation	total	m2a	2.0E+0
air	Carbon dioxide, fossil	total	kg	2.2E-1
air	NMVOC	total	kg	4.4E-4
air	Nitrogen oxides	total	kg	3.6E-3
air	Sulphur dioxide	total	kg	1.0E-3
air	Particulates, < 2.5 um	total	kg	1.3E-3
water	BOD	total	kg	7.0E-4
soil	Cadmium	total	kg	4.6E-7
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-2.6E+0
air	Carbon dioxide, land transformation	low population density	kg	2.7E-5
air	Methane, biogenic	total	kg	4.1E-3
air	Carbon monoxide, biogenic	total	kg	4.3E-1

Tab. 15.18 shows values for CED, non-renewable, fossil for ethanol, 99.7 % in H2O, from sugar cane at distillation, BR and values, which has been found in literature. The values are comparable.

Tab. 15.18 Comparison of CED

	Ethanol 99.7 % from sugar cane at distillation, BR	Ethanol from sugar cane in Brazil (Macedo 1996)	Ethanol from sugar cane in Brazil (Macedo 1998)	Ethanol from sugar cane in Brazil (Macedo 2004)
CED, non-renewable energy resources, fossil (MJ-Eq)	3.6	2.7 – 3.0	3.5	2.9 – 3.0

Appendix: EcoSpold Meta Information



ReferenceFunction	401	Name	ethanol, 99.7% in H2O, from biomass, at distillation
Geography	662	Location	BR
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatio	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Dewatering of ethanol 95% in H2O in Brazil.
	404	Amount	1
	490	LocalName	Ethanol, 99.7% in H2O, aus Biomasse, ab Destillation
	491	Synonyms	Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol//
	492	GeneralComment	The inventory for "ethanol, 99.7% in H2O, from biomass, at distillation, CH" is modelled with ethanol production from sugar cane and molasse from sugar cane in Brazil. Infrastructure is not included, because the process is also done at the fermentation plant. In the electricity input, the usage of heat is included.
	494	InfrastructureIncluded	0
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	C2H6O
	501	StatisticalClassification	
	502	CASNumber	000064-17-5
TimePeriod	601	StartDate	2000
	602	EndDate	2006
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications
Geography	663	Text	The inventory is modelled for Brazil.
Technology	692	Text	Dewatering of ethanol
Representativene	722	Percent	100
	724	ProductionVolume	Total production of ethanol from cane in Brazil is around 16.6 Mio m3 per a.
	725	SamplingProcedure	Literature data.
	726	Extrapolations	
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

15.5 Ethanol, 99.7 % in H_2O from biomass, production BR, at service station, CH

15.5.1 Transport to Switzerland

In North Brazil the ethanol is transported by rail to the port, in the region Centre-South it is transported by pipelines. The average transport distances in Brazil are 100 km by rail and 600 km by pipeline (Tuchschmid 2005). The transport to Europe is calculated as 9710 km by oversea tanker (distance Rio de Janeiro – Rotterdam). The transport to the service station in Switzerland is calculated as 840 km by barge (distance Rotterdam – Basel) and 150 km by lorry 28t according to the standard distances, which are given in Frischknecht et al. (2003).

Tab. 15.19 Total transport services required for the supply of ethanol 99.7% in H_2O from sugar cane BR, at service station, CH

	tkm kg^{-1} ethanol
lorry 28 t	1.50E-01
rail CH	1.00E-01
rail RER	1.00E-01
pipeline onshore	6.0E-01
barge tanker	8.40E-01
transoceanic tanker	9.71

15.5.2 Regional storage

The regional storage is approximated with 2.6E-10 units of “regional distribution, oil products, CH”. The handling at the filling station is assumed with standard factors according to the chapter ”General methodology”: 6.7E-03 kWh electricity, low voltage and 6.21E-04 MJ light fuel oil per kg ethanol.

As emission 5E-04 kg ethanol to air per kg ethanol product is considered. This value is calculated with the standard factors from the chapter “General methodology”. It is assumed that 100% of the electricity consumed, is converted to waste heat and that 100% of the waste heat is released to the air.

All other inputs and outputs are estimated with data of oil products distribution.

A use of nitrogen as cover gas to avoid water uptake is not considered in this report because no information about this is available.

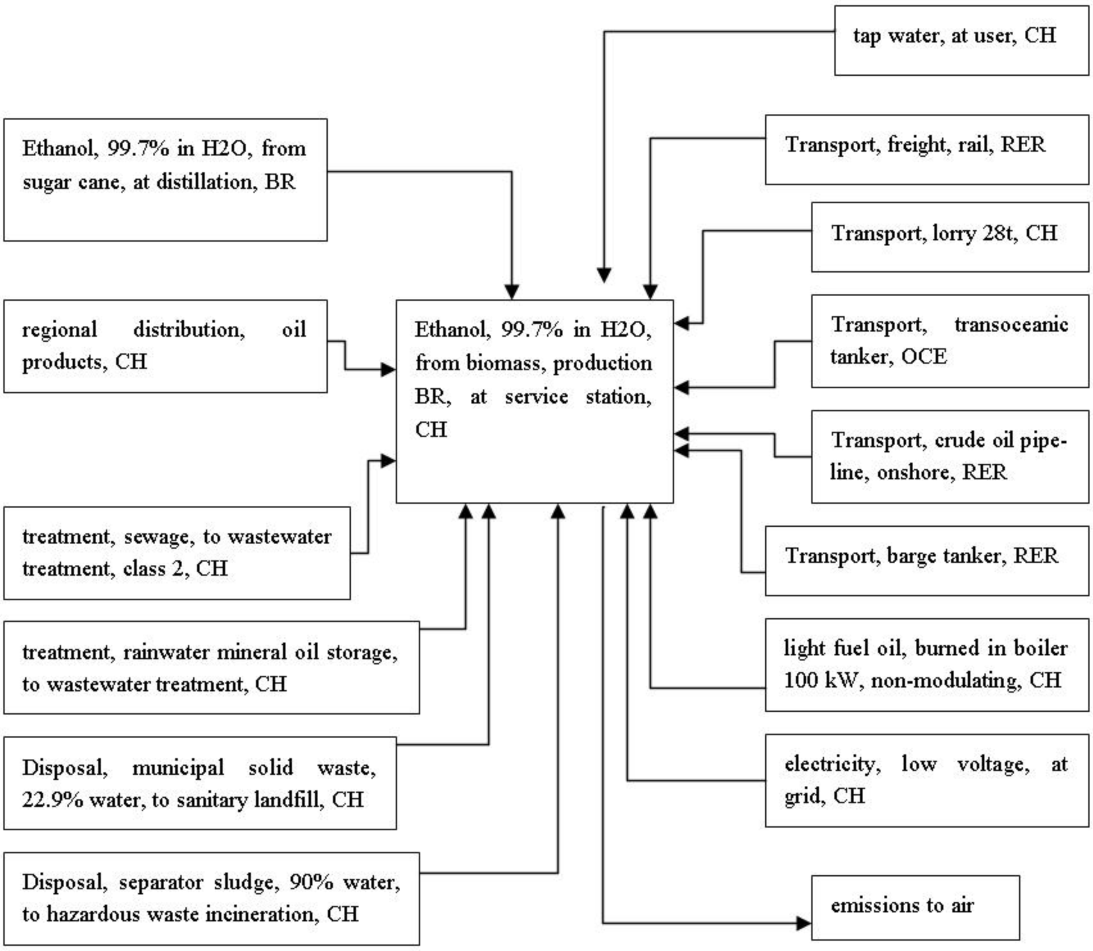


Fig. 15.2 Process flow chart of the production of ethanol from biomass, at service station, CH

15.5.3 Life cycle inventory of the supply of ethanol and data quality considerations

Tab. 15.20 shows life cycle inventory and the data quality indicators of the supply of ethanol, 99.7% in H2O, from biomass, production BR, at service station, CH. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 15.20 Unit process raw data for the supply of ethanol, 99.7% in H2O, from biomass, production BR, at service station, CH

		Location	InfrastructureProcess	Unit	ethanol, 99.7% in H2O, from biomass, production BR, at service	UncertaintyType	StandardDeviation95%	GeneralComment
401	Name							
662	Location				CH			
493	InfrastructureProcess				0			
403	Unit				kg			
	ethanol, 99.7% in H2O, from biomass, production BR, at service station	CH	0	kg	1.00E+0			
technosphere	ethanol, 99.7% in H2O, from biomass, at distillation	BR	0	kg	1.00E+0	1	1.05	(1,1,1,1,1,1); Product plus losses
	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1	1.25	(2,4,1,3,3,3); Estimation according fuel distribution
	tap water, at user	CH	0	kg	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for fuel distribution
	transport, transoceanic tanker	OCE	0	tkm	9.71E+0	1	2.00	(1,1,1,1,1,1); Distance Brazil - Rotterdam
	transport, barge tanker	RER	0	tkm	8.40E-1	1	2.00	(1,1,1,1,1,1); Distance Rotterdam - Basel
	transport, crude oil pipeline, onshore	RER	0	tkm	6.00E-1	1	1.12	(1,3,1,1,1,4); Ethanol-Pipeline in Brazil
	transport, freight, rail	RER	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na); Estimation
	transport, freight, rail	CH	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na); Standard distances
	transport, lorry 28t	CH	0	tkm	1.50E-1	1	2.09	(4,5,na,na,na,na); Standard distances
	regional distribution, oil products	RER	1	unit	2.60E-10	1	3.09	(4,5,na,na,na,na); Estimation
emission air, high population density	Ethanol	-	-	kg	5.00E-4	1	1.58	(3,na,1,3,3,na); Estimation
emission air, high population density	Heat, waste	-	-	MJ	2.41E-2	1	1.14	(2,4,1,3,1,3); Calculated from the electricity input

15.5.4 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 15.21 shows selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from sugar cane BR, at service station.

Tab. 15.21 Selected LCI results and the cumulative energy demand for the supply of ethanol, 99.7% in H2O, from sugar cane BR, at service station, CH

c		Name		ethanol, 99.7% in H2O, from biomass, production BR, at service station
		Location		CH
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.7
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	71.3
LCI results				
resource	Land occupation	total	m2a	2.0E+0
air	Carbon dioxide, fossil	total	kg	3.6E-1
air	NMVOC	total	kg	1.1E-3
air	Nitrogen oxides	total	kg	4.7E-3
air	Sulphur dioxide	total	kg	2.1E-3
air	Particulates, < 2.5 um	total	kg	1.4E-3
water	BOD	total	kg	4.0E-3
soil	Cadmium	total	kg	4.6E-7
Further LCI results				
air	Carbon dioxide, biogenic	total	kg	-2.6E+0
air	Carbon dioxide, land transformation	low population density	kg	2.9E-5
air	Methane, biogenic	total	kg	4.1E-3
air	Carbon monoxide, biogenic	total	kg	4.3E-1

Appendix: EcoSpold Meta Information

ReferenceFunction	401	Name	ethanol, 99.7% in H2O, from biomass, production BR, at service station
Geography	662	Location	CH
ReferenceFunctio	493	InfrastructureProcess	0
ReferenceFunctio	403	Unit	kg
DataSetInformatic	201	Type	1
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctio	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Supply of ethanol from Brazilian production to service stations in Swtzerland including ethanol production and transports.
	404	Amount	1
	490	LocalName	Ethanol, 99.7% in H2O, aus Biomasse, Produktion BR, ab Tankstelle
	491	Synonyms	Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol//
	492	GeneralComment	The inventory for "ethanol, 99.7% in H2O, from biomass, production BR, at CH" is modelled with data of the regional distribution of petrol in Switzerland.
	494	InfrastructureIncluded	1
	495	Category	biomass
	496	SubCategory	fuels
	497	LocalCategory	Biomasse
	498	LocalSubCategory	Brenn- und Treibstoffe
	499	Formula	C2H6O
	501	StatisticalClassification	
	502	CASNumber	000064-17-5
TimePeriod	601	StartDate	2000
	602	EndDate	2005
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	
Geography	663	Text	The inventory is modelled for Switzerland with standard transport distances and standard distribution and data from literature.
Technology	692	Text	Production of ethanol from biomass.
Representativene	722	Percent	100
	724	ProductionVolume	World ethanol production was around 276 Mio hl in 2003.
	725	SamplingProcedure	Literature data.
	726	Extrapolations	Transports are modelled with standard distances.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	ethanol

References

Anselmi 2005a	Anselmi, R. (2005). Novas perspectivas para a biomassa de cana. Jornalcana, 141, 58.
Anselmi 2005b	Anselmi, R. (2005). Tecnologia de concentração de vinhaça e destaque. Jornalcana, 141, 56.
Bichara 1990	Bichara, J. M., & Filho, J. P. (1990). Aspectos Gerais do Gerenciamento Ambiental na Agroindústria canavieira. Paper presented at the I Simpósio Nacional de Gerenciamento Ambiental na Indústria, Brasilia.

Borreroa 2003	Borreroa, M. A. V., et al. (2003). An environmental management method for sugar cane alcohol production in Brazil. Biomass and Bioenergy, 25, 287 – 299.
CDM 2005	Precious Wood Energia Itacoatiara Project. Clean Developement Mechanism: Simplified Project Design Document for small Scale PRoject Activities (SSC-PDD). Itacoatiara, Brazil 2005
CETESB 1988	CETESB. (1988). Planejamento do uso racional das Áreas Agropastoris nas APA's com Destaque para as áreas Canavieiras.São Paulo: Compania de Tecnologia de Saneamento Ambiental -CETESP.
de Reynier 2005	de Reynier, A. (2005). Einsatz von Edra-Rohren zur Verteilung der Vinasse in Zuckerrohrfabriken.Ipeúna, SP, Brasilien.
Dinkel 1998	Dinkel, F., & Real, M. (1998). Treibstoffe aus Biomasse.Basel: Bundesamt für Energie BFE, Bern.
Eners 2006	Eners. Personal communication from Arnaud Dauriad. 31.03.2006
EPA 2006	US Envirnomental Protection Agency. Technology Transfer Network: Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. Fifth Edition 1995. Retrieved 30. March 2006, from http://www.epa.gov/ttn/chief/ap42/index.html
Fernandes 2005	Fernandes, R.: Brazil. Country report. News and information for the Natural Gas Vehicule Industry 2005. Online-Version under: http://www.ngvglobal.com/
Freire 2005	Freire, W. R. (2005). A Hora é agora. ALOOLbrás, Agosto 2005.
Frischknecht et al. 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Galitsky 2003	Galitsky, C., Worrell, E., Ruth, M.: Energy efficiency improvement and cost saving opportunities for the corn wet milling industry. An Energy Star guide for energy and plant managers. Ernest Orlando Berkeley National Laboratory. University of California. Berkeley 2003
Granelli 2005	Granelli, J. (2005). personal Communication. Industria de Alcool e Aguardente, José Granelli & Filhos Ltds, Sitio Sao Benedito Paraisolandia, Charqueada SP, Brazil.
Hassuda 1989	Hassuda, S. (1989). Impactos da Infiltracao da Vinhaca de Cana no Aquifero Bauru. Universidade de São Paulo, Sao Paulo.
IDEA 2005	IDEA. (2005). Mapa das Usinas. Retrieved 29.8.05, 2005, from http://www.ideaonline.com.br/
Isosugar 2005	International Sugar Organization, Quarterly Market Outlook November 2005. Retrieved 31.03.2006 from http://www.isosugar.org
JornalCana 2005	JornalCana. (2005). Demanda pro álcool deve aumentar área de cana em 3 milhões de hectares. Jornalcana, p. 32.
Macedo 1996	Macedo, I. d. C. (1996). Greenhouse Gas Emissions and Avoided Emissions in the Production and Utilization of Sugar Cane, Sugar and Ethanol in Brazil: 1990-1994. from http://www.mct.gov.br/clima/ingles/comunic_old/coperal.htm

Macedo 1998	Macedo, I. d. C. (1998). Greenhouse gas emissions and energy balances in bio-ethanol Production and utilization in Brazil (1996). Biomass and Bioenergy, 14, 77-81.
Macedo et al. 2004	Macedo, I. d. C., et al. (2004). Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil.São Paulo: Government of the State of São Paulo, Secretariat of the Environment.
Marcello 2005	Marcello. (2005). Neue Lösungen zur Wasserreduktion in modernen Usinas.
Mathias 2005a	Mathias, J. (2005). Anos Dourados para a indústria de cana. Globo Rural, Ediçao Especial, 10.
Mathias 2005b	Mathias, J. (2005). A refinaria do futuro. Globo Rural, Ediçao Especial, 46.
Möllersten 2003	Möllersten, K., et al. (2003). Potential market niches for biomass energy with CO2 capture and storage--Opportunities for energy supply with negative CO2 emissions. Biomass and Bioenergy, 25(3), 273-285.
Moreira 2000	Moreira, J. R. (2000). Sugarcane for energy - recent results and progress in Brasil. Energy for Sustainable Development, 4(3).
Moreira 1999	Moreira, J. R., & Goldemberg, J. (1999). The alcohol program. Energy Policy, 27(4), 229-245.
Percebon 1985	Percebon, C. M., & Vallo de Amaral, L. A. (1985). Avaliacao da Qualidade das águas de Lavagem de Cana recilcadas em duas usinas do estado de São Paulo. Paper presented at the 13. Congresso Brasileiro de Engenharia Sanitária e Ambiental, Maceió - Alagoas.
Recco 2005a	Recco, R. (2005). Começa a operar em Santos terminal exclusivo para etanol. Paraná Açúcar & Álcool, Setembro, 11.
Recco 2005b	Recco, R. (2005). A retomada do álcool combustivel. Paraná Açúcar & Álcool, Setembro, 11.
dos Santos 1997	dos Santos, M.: Energy analysis of crops used for producing ethanol and CO2 emissions. Energy Planning Program/COPPE/UFRJ. Rio de Janeiro 1997
Tuchschmidt 2005	Tuchschmid, Matthias, Steiner, Stefanie: Personal communication. Ipeuna, Brazil 2005
UNICA 2004	UNICA. (2004). Brazil's Sugar and Ethanol - Energy and Environmental Commodities.Saõ Paulo.
UNICA 2005	UNICA. (2005). Carro a álcool - Mercado. Retrieved 8. September, 2005, from http://www.portalunica.com.br/acao/combustivel.jsp

16 Ethanol-based biofuels

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Summary

The present chapter deals with the life cycle inventory of fuel-ethanol and related processes. The expression ‘ethanol-based biofuels’ here refers to fuel-bioethanol and bioethanol-based fuels (for use in the transportation sector) derived from the processing of various biomass resources (sugar beet molasses, potatoes, wood, rye, corn, sugarcane molasses, sweet sorghum). The datasets described in this chapter include hydrated bioethanol (95% wt. in H_2O), anhydrous bioethanol (99.7% wt. in H_2O), ETBE, E5 and E85 (blends of 5% vol., resp. 85% vol., bioethanol with gasoline), as well as blends of ETBE and gasoline (4% vol., resp. 15% vol., ETBE with gasoline). Ethanol may result as the main production of biomass fermentation or as a by-product of sugar production. Associated by-products are also included.

16.1 Introduction

Bioethanol is an alternative fuel, used as an additive or partial substitute to conventional or ‘fossil’ gasoline, which can be produced from various biomass resources (including sugar-based, starch-based and more recently, cellulosic biomass). Since the mid-1970's, the production and use of bioethanol as a fuel has grown significantly, especially in Brazil (BR), the United States (US), the European Union (EU), Canada (CA) or China (CN). The production process and use of bioethanol is described in more detail in the following sections.

This chapter documents the life cycle inventories for ethanol-based fuel systems contained in ecoinvent data v2.0. The processes relating to ethanol-based biofuels covered in this study data are summarized in Tab. 16.1 below. The datasets are divided into three main groups, namely 'sugar', 'ethanol' and 'ethanol/ETBE- gasoline blends. The locations, categories, sub-categories and units are indicated for each of the datasets. Datasets shown in light text over dark background indicate multi-output (MO) processes. Datasets with an indentation are the outputs of the above MO-processes.

Tab. 16.1 Overview of the 'ethanol-based biofuels' datasets covered within the ecoinvent database.

Name	Location	Category	SubCategory	unit
Sugar				
sugar refinery	GLO	food industry	processing	unit
sugar beet, in sugar refinery	CH	food industry	processing	kg
sugar, from sugar beet, at sugar refinery	CH	food industry	processing	kg
pulps, from sugar beet, at sugar refinery	CH	biomass	others	kg
molasses, from sugar beet, at sugar refinery	CH	biomass	others	kg
sugarcane, in sugar refinery	BR	food industry	processing	kg
sugar, from sugarcane, at sugar refinery	BR	food industry	processing	kg
ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery	BR	biomass	fuels	kg
electricity, bagasse, sugarcane, at sugar refinery	BR	biomass	cogeneration	kWh
vinasse, from sugarcane molasses, at sugar refinery	BR	biomass	others	kg
bagasse, from sugarcane, at sugar refinery	BR	biomass	others	kg
Ethanol				
potatoes, in distillery	CH	biomass	fuels	kg
ethanol, 95% in H2O, from potatoes, at distillery	CH	biomass	fuels	kg
DDGS, from potatoes, at distillery	CH	biomass	others	kg
corn, in distillery	US	biomass	fuels	kg
ethanol, 95% in H2O, from corn, at distillery	US	biomass	fuels	kg
DDGS, from corn, at distillery	US	biomass	others	kg
ethanol, 99.7% in H2O, from biomass, at distillation	US	biomass	fuels	kg
ethanol, 99.7% in H2O, from biomass, production US, at service station	CH	biomass	fuels	kg
sweet sorghum, in distillery	CN	biomass	fuels	kg
ethanol, 95% in H2O, from sweet sorghum, at distillery	CN	biomass	fuels	kg
electricity, bagasse, sweet sorghum, at distillery	CN	biomass	cogeneration	kWh
vinasse, from sweet sorghum, at distillery	CN	biomass	others	kg
bagasse, from sweet sorghum, at distillery	CN	biomass	others	kg
ethanol, 99.7% in H2O, from biomass, at distillation	CN	biomass	fuels	kg
ethanol, 99.7% in H2O, from biomass, production CN, at service station	CH	biomass	fuels	kg
rye, in distillery	RER	biomass	fuels	kg
ethanol, 95% in H2O, from rye, at distillery	RER	biomass	fuels	kg
DDGS, from rye, at distillery	RER	biomass	others	kg
ethanol, 99.7% in H2O, from biomass, at distillation	RER	biomass	fuels	kg
ethanol, 99.7% in H2O, from biomass, production RER, at service station	CH	biomass	fuels	kg
molasses, from sugar beet, in distillery	CH	biomass	fuels	kg
ethanol, 95% in H2O, from sugar beet molasses, at distillery	CH	biomass	fuels	kg
syrup, from sugar beet molasses, at distillery	CH	biomass	others	kg
wood, in distillery	CH	biomass	fuels	kg
ethanol, 95% in H2O, from wood, at distillery	CH	biomass	fuels	kg
electricity, wood, at distillery	CH	biomass	power plants	kWh
Ethanol/ETBE-gasoline blends				
petrol, 5% vol. ethanol, from biomass, at service station	CH	oil	fuels	kg
petrol, 85% vol. ethanol, from biomass, at service station	CH	biomass	fuels	kg
ethyl tert-butyl ether, from bioethanol, at plant	RER	biomass	fuels	kg
petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery	RER	oil	fuels	kg
petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	CH	oil	fuels	kg
petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery	RER	oil	fuels	kg
petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	CH	oil	fuels	kg

The chapter is structured as follows:

- Section 16.2 (Resources of sugar and ethanol) provides some general information on the availability of feedstocks for bioethanol production, both worldwide and in the Swiss context.
- Section 16.3 (Characterisation of ethanol-based biofuels) presents the most significant chemical and physical properties of ethanol-based biofuels for use in the transportation sector. The properties are compared to those of conventional gasoline, with which these fuels compete.
- Section 16.4 (Use and application of ethanol-based biofuels) describes the uses of the various ethanol-based biofuels described in this chapter. Other possible uses of ethanol are mentioned.
- Sections 16.5 to 16.13 describe the actual datasets considered in the present chapter, including system characterization (definition of the system boundaries, technical description of the production process, interactions of the various products and by-products and allocation issues of multi-output processes) and life cycle inventory.
- Section 16.14 discusses the quality of the life cycle inventories presented in this chapter.

- Section 16.15 (Cumulative results and interpretation) presents and discusses LCI results and values for the cumulative energy demand of selected processes in this chapter. These results are compared to similar results published in related articles and reports.
- Section 16.16 finally gives the conclusions.

16.2 Resources of sugar and ethanol

16.2.1 Resources of sugar

Sugar or sucrose is extracted from plant sources. The most important two sugar crops are sugarcane (Saccharum spp.) and sugar beets (Beta vulgaris), in which sugar can account for 12% to 20% of the plant's dry weight. In 2000, around 130 million tons of sugar were produced worldwide (Tab. 16.2).

Tab. 16.2 World sugar production for the period 1990-2000 and projections for 2006 and 2010 (Koizumi 2003).

Region	Sugar production (million tons)					Growth rate (%/yr)	
	1990	1995	2000	2006	2010	1990/2000	2000/2010
World Total	**110.51**	**117.92**	**130.76**	**147.05**	**156.69**	**1.5**	**1.7**
Brazil	7.94	13.59	17.04	23.31	25.57	7.2	3.8
OECD countries Total	32.21	33.46	36.4	37.39	38.79	1.1	0.6
United States	6.34	6.69	7.88	8.02	8.34	2	0.5
EU 15	17.98	16.53	17.64	17.85	18.54	-0.2	0.5
Australia	3.68	5.06	5.45	5.38	5.77	3.6	0.5
Mexico	3.28	4.27	4.7	5.33	5.32	3.3	1.1
Japan	0.93	0.91	0.73	0.82	0.83	-2.2	1.2
India	11.76	16.41	20.22	21.5	22.46	5.1	1
China, Mainland	6.88	6.77	6.74	8.25	8.99	-0.2	2.7
Cuba	8.04	3.26	4.06	4.01	4.08	-6	0
ACP Countries	5.86	6.03	6.73	7.62	8.14	1.3	1.7
South Africa	2.03	1.67	2.66	2.82	3.18	2.5	1.6
Thailand	3.51	5.2	6.45	7.74	8.03	5.7	2
Former USSR	9.43	6.61	4.15	4.81	5.07	-7.2	1.8

In interpreting Tab. 16.2, the reader should be aware that the regions selected include both individual countries and groups which may overlap, and therefore all the lines do not sum up to the World total.

The major cane sugar producing countries are countries with warm climates, such as Brazil, India, China and Australia (in descending order). The sugar beet regions are in cooler climates: north- west and eastern Europe, northern Japan, plus some areas in the United States including California[37].

In Switzerland, the sugar refineries of Aarberg and Frauenfeld have processed 1.4 million tons of sugar beets during the 2004-2005 campaign, resulting in the production of some 220 thousand tons of sugar and 42 thousand tons of molasses and 330 thousand tons of pulps.

16.2.2 Resources of ethanol

There is a lot of confusion surrounding the production of and trade in ethanol. This is hardly surprising given that there are a variety of feedstocks from which it can be produced, a number of production processes and very different uses for this commodity, usually classified into fuel, industrial and beverage uses (Berg 2004).

The largest single use of ethanol since the 1990's is as a motor fuel and fuel additive (Fig. 16.1).

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[37] Wikipedia, The Free Encyclopedia. Retrieved in April 2006 from http://en.wikipedia.org.

In 2004, total production of bioethanol fuel worldwide was 32'000 million litres (Ml). The largest national fuel ethanol industries exist in Brazil (47%) and the US (40%). In 2004, about 12’500 Ml of fuel-ethanol (from sugarcane) were consumed in Brazil and 2'500 Ml were exported at an average price of 0.21 US$/l. India was the first importer of Brazilian ethanol (23%) followed by the US (20%). In the US, fuel-ethanol production (from corn) grew from virtually nothing in 1980 to 12’900 Ml in 2004. Although Brazil (BR) and the US produced about 87% of fuel-ethanol worldwide in 2004, other countries and regions are emerging and should play a significant role in the future market. The EU has produced 620 Ml in 2004, mostly from sugar beets and cereals. Asia is another region where fuel-ethanol market is growing very fast. China has launched fuel-ethanol programmes in a few provinces based on corn starch, while India and Thailand are also experiencing such ethanol programmes at a large scale (Gnansounou & Dauriat 2005).

In Switzerland, 12 Ml of ethanol were produced from wood cellulose (as a by-product of pulp and paper, by the company Borregaard) in 2005, of which 1 Ml (0.8 kt) were used as a fuel.

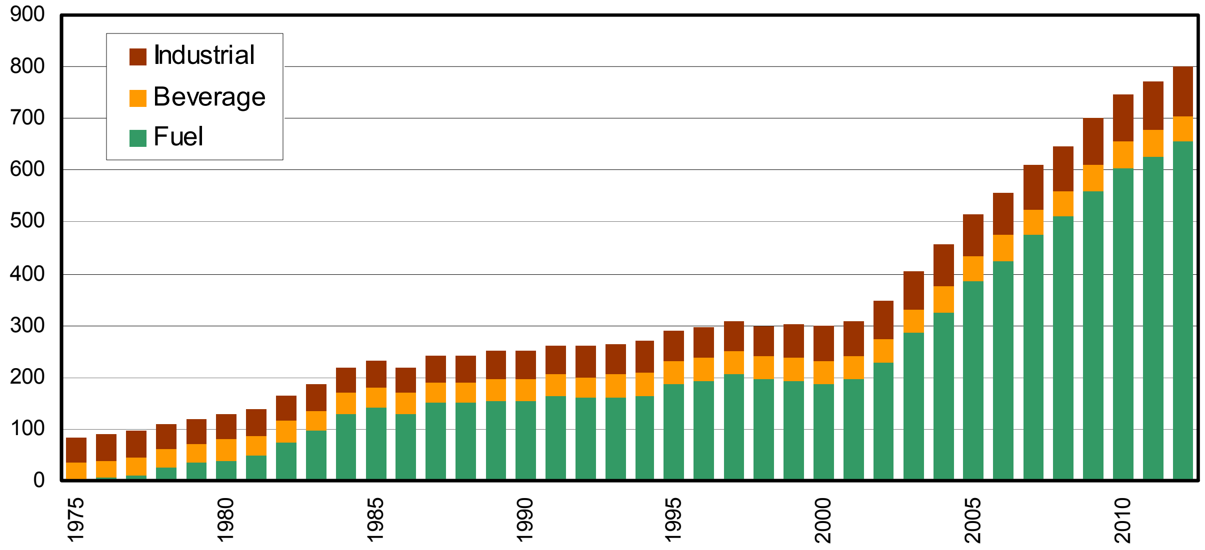

Fig. 16.1 World ethanol production (in Mt/yr) for the period 1975-2004 and projections until 2012 (Berg 2004).

The demand for fuel-ethanol is expected to grow very fast till 2012 (Fig. 16.1), with driving factors such as: (1) the ban of MTBE in gasoline and new legislation favourable to biofuels in the US; (2) the fast growth of Flexible Fuel Vehicles in Brazil and in other countries; (3) the European Directive on motor biofuels; and (4) the introduction of E10 (ethanol-gasoline blend consisting of 10% vol. ethanol and 90% vol. gasoline) in China and likely in India, Thailand and other Asian countries.

Tab. 16.3 World ethanol production for the period 1990-2000 (Koizumi 2003).

Region	Ethanol production (thousand tons)					Growth Rate (%/yr)	
	1990	1995	2000	2006	2010	1990/2000	2000/2010
World Total	**18'391**	**19'418**	**19'284**	**-**	**-**	**0.4**	**-**
Brazil	12'028	12'700	10'900	-	-	-0.9	-
OECD Countries	3'487	3'789	5'129	-	-	3.6	-
United States	2'216	2'540	3'999	-	-	5.5	-
EU 15	1'144	1'121	1'002	-	-	-1.2	-
Mexico	126	128	128	-	-	0.1	-
India	1'175	1'434	1'985	-	-	4.9	-
China, Mainland	43	125	200	-	-	15.1	-
ACP Countries	14	18	21	-	-	3.8	-
Thailand	77	86	90	-	-	1.4	-
Former USSR	191	393	263	-	-	2.9	-

In interpreting Tab. 16.3, the reader should be aware that the regions selected include both individual countries and groups which may overlap, and therefore all the lines do not sum up to the World total.

The world demand of fuel-ethanol in 2015 could amount to about 65'000 million litres, about twice the demand in 2004. The US and Brazil would account for 30% each followed by the European Union (15%), Asia (15%) and the rest of the world (10%). To meet this demand, the international trade would progress with Brazil as the major player. The Brazilian exports could grow from 2'500 million litres in 2004 to 6'000 million litres in 2015 (Gnansounou & Dauriat 2005).

China, but also Thailand, India and Japan have now launched their national gasohol (fuel blend consisting of 10% vol. ethanol and 90% vol. gasoline) policies. Thailand started blending 10% ethanol with gasoline in 1985; now there are more than 4000 stations serving E10. The blending of 10% ethanol into gasoline will be mandatory by the end of 2006 with the import ban on MTBE. It is expected that once the production of ethanol from cassava and sugarcane molasses can be ramped up, a higher blending ratio like E20 or E85 or even Flexible Fuel Vehicle will be introduced to Thailand.

16.3 Characterisation of ethanol-based biofuels

Pure (100% wt.) ethanol (ethyl alcohol, C_2H_5OH, melting point –114°C, boiling point 78.4°C, CAS No. 000064-17-5) is soluble in water and has a density of 0.789 kg/l at 20°C.

In the field of ethanol, the distinction between anhydrous and hydrated qualities is of major importance. Anhydrous alcohol is free of water and at least 99% (wt.) pure. This quality of ethanol may be used in fuel blends (e.g. as a mixture with gasoline). Hydrated ethanol, on the other hand, contains some water and usually has a purity of 95-96% (wt.). In Brazil, this quality of ethanol is being used as a gasoline substitute in cars with dedicated engines. This distinction between anhydrous and hydrated ethanol is indeed of relevance, not only in the transportation sector, and may be regarded as the basic quality distinction in the ethanol market.

In this study, two blends of ethanol with conventional gasoline are considered, namely (1) E5 (5% vol. anhydrous ethanol mixed with 95% vol. gasoline) and (2) E85 (85% vol. anhydrous ethanol mixed with 15% gasoline). The use of these blends is described in more detail in section 16.4 on the use and applications of ethanol-based biofuels.

Anhydrous ethanol can also be reacted with isobutene (product of oil refineries, TBA plants and/or merchant plants) to produce ETBE (ethyl tert-butyl ether), consisting of 47% wt. ethanol and 53% wt. isobutene. Just like anhydrous ethanol, ETBE can be used as a substitute of octane enhancers in conventional gasoline, and can be incorporated to gasoline at up to 15% vol. (corresponding to the maximum ether content according to the European Norm EN-228 on the quality of gasoline). The average content of ethers in gasoline in the EU today is 4% vol. Blends of ETBE with gasoline have been experienced in the US, Germany, Czech Republic, Italy, the Netherlands, Poland, Finland, Portugal, and represent the single largest use of fuel-ethanol in France and Spain. The incorporation of ETBE to gasoline is also considered, at rates of 4% vol. (the typical average in Switzerland) and 15% vol. (the maximum rate allowed according to the European norm).

The main characteristics of ethanol-based biofuels as described in this study are given in Tab. 16.4.

Tab. 16.4 Main characteristics of ethanol-based biofuels as described in this study.

basic unit in the database		ethanol, 95% in H2O kg pure etOH	ethanol, 99.7% in H2O kg pure etOH	ETBE, from etOH kg	petrol, 5% etOH kg	petrol, 85% etOH kg	petrol, 4% ETBE kg	petrol, 15% ETBE kg
Lower heating value (LHV)	MJ	26.8	26.8	35.9	41.7	29.1	42.2	41.5
Higher heating value (HHV)	MJ	29.7	29.7	39.5	44.3	31.9	44.9	44.3
Density 20°C	kg/l	0.789	0.789	0.75	0.752	0.783	0.75	0.75
Oxygen	kg	0.348	0.348	0.163	0.021	0.298	0.009	0.027
Carbon, fossil	kg	0.000	0.000	0.454	0.820	0.124	0.849	0.803
Carbon, biogen	kg	0.522	0.522	0.245	0.027	0.447	0.010	0.037
Hydrogen	kg	0.130	0.130	0.137	0.135	0.131	0.135	0.135
CO2 Factor	kg/MJ	0.0714	0.0714					
CO2 Factor	kg	1.9130	1.9130					
Formula		C_2H_6O	C_2H_6O	$C_6H_{14}O$				
CAS		64-17-5	64-17-5	637-92-3				

The reasons generally accepted behind the success of fuel-ethanol are: (1) use as alternative fuel for reducing CO_2 emission and limiting risk of climate change; (2) use as renewable energy resource to partly substitute oil and increase security of supply in the transportation sector; (3) use as an oxygenated compound for cleaner combustion of the gasoline and improved urban air quality; and (4) use as octane enhancer in unleaded gasoline in place of methyl tert-butyl ether (MTBE), benzene or metallic additives like lead. The first two points listed above are actually to be proven through LCI and LCIA studies like the present one.

16.4 Use and applications of ethanol-based biofuels

Certainly the oldest form of use of alcohol is that of a beverage. The most important market for ethanol as an industrial application are solvents, used primarily in the production of paints and coatings, dyes, perfumes, pharmaceuticals, adhesives inks, etc. Ethanol indeed represents one of the major oxygenated solvents in this category. Production and consumption is concentrated in the industrialized countries in Northern America, Europe and Asia. It is the only industrial application where synthetic ethanol holds a significant market share (Berg 2004), as it is cheaper than ethanol derived from biomass. Bioethanol however captures the alcoholic beverages market and the fuel-ethanol market. Ethanol intended to non-food uses is made unfit for human absorption by addition of small amounts of toxic or unpleasant substances such as methanol or gasoline.

The use and applications of ethanol in this report concentrates on the fuel market. The following two paragraphs describe the use of ethanol-based biofuels in internal combustion engines.

16.4.1 Use in spark-ignition internal combustion engines

Ethanol has good properties for spark ignition internal combustion (IC) engines (i.e. gasoline engine). Its Motor Octane Number (MON) and Research Octane Number (RON) are 90 and 109 respectively, leading to an average octane index of 99 compared to 88 for conventional gasoline. Fuel-ethanol may be used in IC engines in various ways, namely:

- in standard (unmodified) gasoline engines, as blends of up to 26% (vol.) anhydrous ethanol with gasoline (5% max. in EU and India, 10% in the US, 22-26% mandatory blends in Brazil);

- in standard (unmodified) gasoline engines, as blends of up to 15% (vol.) ETBE with gasoline (15% max. in Europe);
- in flexible-fuel vehicles, as blends of up to 85% (vol.) anhydrous ethanol with gasoline;
- in dedicated ethanol vehicles, as neat hydrated ethanol (Brazil only).

Dedicated ethanol vehicles are optimised so that the engine efficiency is improved by running at higher compression ratios to take advantage of the better octane index of ethanol compared to gasoline. In such conditions, hydrated fuel-ethanol can achieve about 75% or more of the fuel economy of gasoline (km/l), even though the lower heating value (LHV) of ethanol (21.3 MJ/l or 26.8 MJ/kg) is two-thirds that of gasoline (31.9 MJ/l or 42.5 MJ/kg).

Flexible-fuel vehicles (FFVs) are equipped with line sensors, which measure the level of ethanol in the fuel blend and adapt the air-to-fuel ratio accordingly to maintain optimum combustion conditions. These vehicles can burn ethanol-gasoline fuel blend containing up to 85% (vol.) ethanol. They are becoming more and more frequent in Brazil and Sweden with various manufacturers developing such vehicles on a commercial scale. Since the compression ratio cannot be adapted in case of FFVs, the increase of the fuel consumption is somewhat proportional to the content of ethanol in the fuel blend.

The use of fuel-ethanol in IC engines, however, shows a few disadvantages: (1) low-level ethanol blends show an increase of the vapour pressure (RVP), which favours evaporative emissions and contributes to smog formation, and (2) high-level ethanol blends show a significant drop of the vapour pressure (RVP), leading to difficulties in cold weather conditions.

16.4.2 Use in compression-ignition internal combustion engines

Due to its low cetane number, ethanol does not burn efficiently by compression-ignition IC engines (i.e. diesel engines). Moreover, ethanol is not easily miscible with diesel fuel. Three directions are followed to improve the use of ethanol in diesel engines, namely:

- in standard (unmodified) diesel engines, as blends of up to 15% (vol.) anhydrous ethanol with diesel (E-diesel);
- in adapted (dual-fuel operation) diesel engines, where ethanol and diesel are introduced separately into the cylinder;
- in adapted diesel engines, as neat hydrated ethanol.

The blending of anhydrous ethanol with diesel requires the addition of an emulsifier (to improve ethanol-diesel miscibility) and of other additives such as ethylhexylnitrate or diterbutyl peroxide (to enhance the cetane number). Most ethanol-diesel blends are limited to 15% ethanol and 5% emulsifiers.

Although many trials have been conducted in real conditions (especially in Scandinavian countries), the use of ethanol in compression-ignition (CI) engines is still at the experimental level.

16.5 Ethanol from sugar beet molasses, CH

16.5.1 System characterization

The system described in this paragraph includes the production of sugar, molasses and pulps from sugar beet, and the production of hydrated ethanol (95% vol.) and syrup, from sugar beet molasses in the Swiss context (Fig. 16.2). The dehydration to ethanol 99.7% wt. is described in chapter 14.9 "Ethanol, 99.7 % in H_2O from biomass, at distillation, CH”.

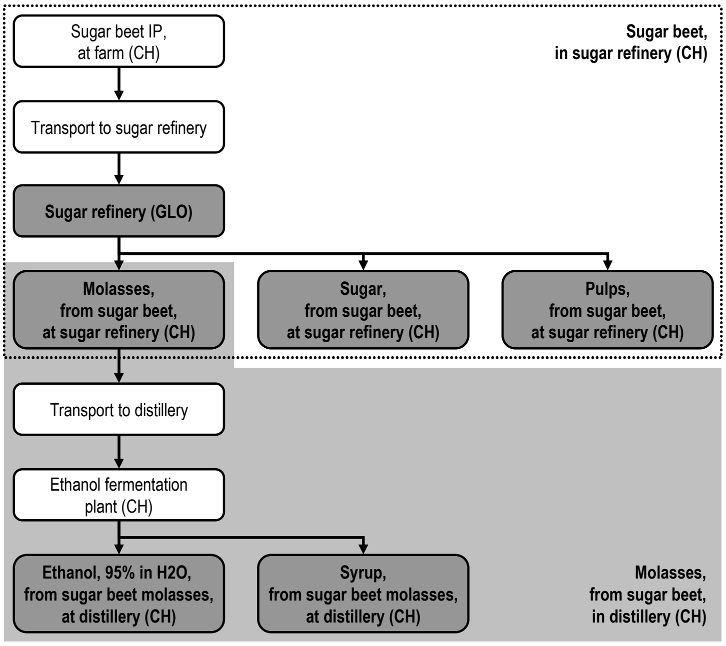

Fig. 16.2 Ethanol from sugar beet molasses, CH: system definition and boundaries.

The processes shown in dark boxes indicate datasets actually described and developed in this chapter. The dashed line and the shaded area show the boundaries of the multi-output (MO) processes 'Sugar beet, in sugar refinery' and 'Molasses, from sugar beet, in distillery' respectively. The two processes are described in two paragraphs below.

Sugar beet, in sugar refinery (CH)

The production of sugar, molasses and pulps from sugar beet is based on the technology of the sugar refinery in Aarberg and data from (ZAF 2002) and (Poitrat 1998). This paragraph describes the technology and yields of the various outputs. The allocation issue is also addressed.

In Switzerland, sugar beets are mostly delivered by rail to the sugar refinery. Upon arrival (1), the beets are unloaded with large water hoses and either stored into silos or dumped directly into wet hoppers. Before reaching the actual washing station (2), the beets pass through a rock-catcher for the removal of any rocks, mud or sand trash, and then through another section for the removal of trash, weeds or leaves. From the washer, the beets are fed to the slicers, where they are cut into pieces called "cossettes". Leaving the slicers, the cossettes are carried across a weighing device and discharged into a scalding tank leading to the diffuser.

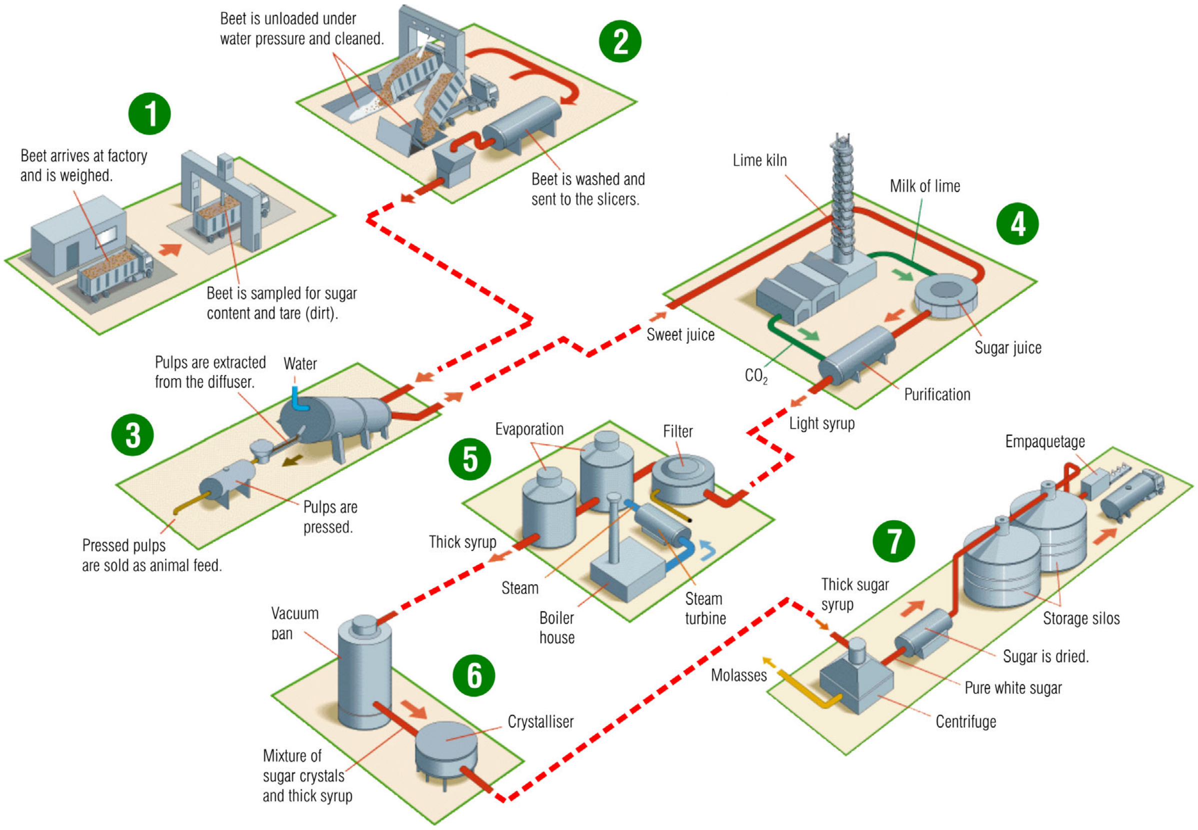

Fig. 16.3 Schematic representation of the production sugar from beets (adapted from Irish Sugars 2006).

In the diffuser (3), the sugar is extracted from the cossettes by continuous diffusion in hot water. The hot water enters the opposite end to that of the cossettes, giving a counter-current effect which improves the extraction rate. The sugar solution (sweet juice) and the pulps (free of most of the sugar) are collected at the two opposite ends of the diffuser (see Fig. 16.3). The pulps are pressed down to 75% water and sold as animal feed.

As it leaves the diffuser, the sweet juice contains about 84% water, 1.5% non sugars and 14.5% sugars. Before sugar can be produced in a white crystalline form, it is necessary to remove as many of the non-sugars as possible. This part of the process is referred to as the juice purification stage (4). The main input here is limestone which is burnt in a kiln to produce a milk of lime and carbon dioxide. These substances are added to the solution, causing non-sugars to be precipitated out of the solution. The solid material is then filtered off, leaving the juice with a light yellow colour.

The purified juice is first concentrated by boiling off water from the solution in evaporators, resulting in a 60% sugar solution, often termed light syrup (5). More water is then evaporated by feeding the syrup to vacuum pans, where crystals start to form within the syrup (6). This mixture of crystals and syrup (often referred to as thick syrup) is discharged into large crystallisers. The crystals are finally separated from the residual slurry (molasses) by centrifuge (7), then dried and finally stored in silos before packaging. Molasses, consisting of 50% sugars, 32% non-sugars and 18% water, may be used as cattle feed or as a feedstock for fuel-ethanol production.

According to the data in Tab. 16.8, more specifically from the sugar refinery in Aarberg (ZAF 2002), 1 ton of clean sugar beets (17% sugars, 6% non-sugars and 77% water) results in:

- 156.9 kg of pure white sugar (100% dry matter);
- 35.9 kg of molasses (50% sugars, 32% non-sugars, 18% water);
- 204.0 kg of pressed pulps (25% dry matter, 75% water).

According to (ZAF 2005), the sugar refinery in Aarberg processed 686'000 tons of sugar beets during the 2004-2005 campaign, and produced 108'000 tons of sugar (157 kg/t beets), 163'500 tons of pressed pulps (238 kg/t beets) and 20'600 tons of molasses (30 kg/t beets). However, the yields from (ZAF 2002) are preferred and used in this report, because they match the data for raw materials and energy consumption.

The prices of sugar, pressed pulps and molasses are taken as 1'000 CHF/t, 35 CHF/t and 240 CHF/t respectively (ZAF 2002). The resulting allocation factors are indicated for each group of process stages in Tab. 16.5.

Tab. 16.5 Allocation factors in the production of sugar from sugar beets (CH).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Washing Slicing Diffusion	Sugar	91.7%	70.2%	51.9%	71.9%
	Beet pulps	3.8%	19.2%	36.3%	18.5%
	Molasses	4.5%	10.6%	11.9%	9.6%
Pressing of pulps	Sugar	0.0%	0.0%	0.0%	0.0%
	Beet pulps	100.0%	100.0%	100.0%	100.0%
	Molasses	0.0%	0.0%	0.0%	0.0%
Purification Crystallisation	Sugar	95.3%	86.9%	81.4%	88.2%
	Beet pulps	0.0%	0.0%	0.0%	0.0%
	Molasses	4.7%	13.1%	18.6%	11.8%

Molasses, from sugar beet, in distillery (CH)

The description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse, more particularly from the business plan of the multi-feedstock ethanol plant designed in the frame of that project (ENERS 2005; INTERIS 2002). The ethanol plant considered here processes 162 kt/yr of molasses, and produces approx. 42 kt/yr of hydrated ethanol (95% wt.) as well as 100 kt/yr of stillage syrup (58% wt. dry matter). The quantities of molasses envisaged are actually larger than the present production in Switzerland (approximately 42 kt/yr in 2005), and therefore significant amounts of molasses would actually have to be imported according to the present situation. In this study, the necessary imports are modelled as if produced in Switzerland, in the Swiss conditions.

The production plant described here is supposed to be operating approximately 336 days/yr. Molasses, for having a high sugar concentration (50% wt.) can indeed be stored for relatively long periods.

The fermentation unit aims at producing a beer (or wine) at 9% (vol.) ethanol. Fermentation operates in a continuous mode and comprises two steps: (1) the pre-fermentation of a fraction of the molasses, to produce the required yeasts for fermentation, and (2) the fermentation itself, aiming at converting the sugars into ethanol by means of the yeasts. The fermentation lasts for 30-35 hours.

The distillation unit aims at producing a hydrated ethanol at up to 95% (vol.). The unique distillation column operates at low temperature and in vacuum, in order to avoid possible clogging problems. As opposed to the corn process, the stillage is sent directly, as such, to the pre-concentration unit, without a clarification/separation stage. The distillation is coupled to the pre-concentration unit, in order to reduce the global energy consumption. Hence, the distillation column is heated by direct injection of the steam produced in the first evaporator effect of the pre-concentration unit.

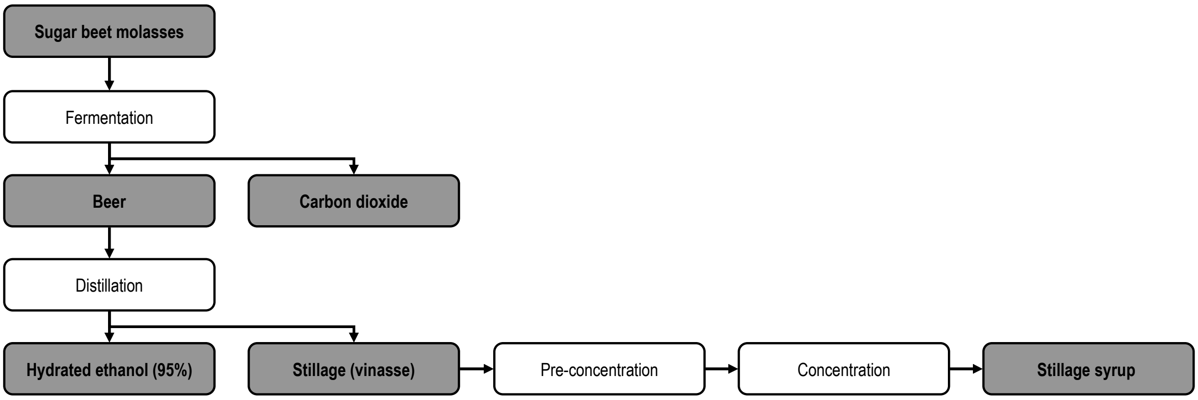

Fig. 16.4 Production stages for the processing or sugar beet molasses to hydrated ethanol and stillage syrup.

The pre-concentration unit aims at concentrating the stillage by evaporation. The evaporation is realized in a double-effect counter current unit, each effect comprising a group 'evaporator-separator' with forced recirculation. The second effect is heated by steam coming from the boiler, and the evaporation steam, in turn, heats the first effect. The evaporation steam of the first effect provides the heat for the distillation stage by direct injection. The net consumption of plant steam in pre-concentration, and hence the concentration of dry matter at the exit, depend directly on the quantity of steam required in distillation (therefore also on the ethanol concentration of the fermented mash).

The concentration unit aims at concentrating further the dilute syrup in order to produce a concentrated syrup at about 55-60% dry matter (Fig. 16.4). This by-product is utilized as animal feed. Concentration is realized in a 4-effect counter current unit. Like in the pre-concentration, the fourth effect is heated with steam from the plant, while the evaporated water in turn heats the third effect and so on.

According to the data from Tab. 16.10, 1 ton of sugar beet molasses (50% sugars, 32% non-sugars, 18% water) results in:

- 245.3 kg of hydrated ethanol (95% wt., dry basis);
- 614.3 kg of stillage syrup (58% dry matter, 42% water).

Allocation between ethanol and syrup is performed, based on the estimated market prices (ENERS 2005) of anhydrous ethanol (i.e. 1.40 CHF/l) and stillage syrup (i.e. 120 CHF/t) in Switzerland. The resulting allocation factors are indicated for each group of process stages in Tab. 16.6.

Tab. 16.6 Allocation factors in the production of ethanol from sugar beet molasses (CH).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Fermentation Distillation	Hydrated ethanol	94.5%	55.9%	7.4%	60.1%
	Stillage syrup	5.5%	44.1%	92.6%	39.9%
Stillage treatment	Hydrated ethanol	0.0%	0.0%	0.0%	0.0%
	Stillage syrup	100.0%	100.0%	100.0%	100.0%

16.5.2 LCI of 'Sugar refinery, GLO'

The infrastructure process 'sugar refinery' includes land transformation and occupation, buildings and facilities of a typical sugar refinery in the global context (GLO). Energy use for construction and related emissions and/or waste effluents are not included.

The sugar production capacity of the refinery described in this inventory is 200’000 t/yr over a period of 100-180 days, depending on the feedstock. The equivalent feed capacities vary from 1’300 kt/yr for sugar beets to 1’650 kt/yr for sugarcane. The considered lifetime of the sugar refinery is 50 years.

Due to a lack of data, the dataset ‘sugar refinery’ is based on the dataset ‘ethanol fermentation plant’, describing the inventory of an ethanol plant of a production capacity of 90’000 t/yr (corresponding to 180’000 t/yr of sugar). A factor of 2/1.8 is applied to all inputs (incl. resources and technosphere) and emissions. The occupation of land is adapted to the lifetime considered.

The unit process raw data of 'sugar refinery’ is indicated in Tab. 16.7.

Tab. 16.7 Unit process raw data of the dataset ‘sugar refinery’, GLO.

	Name	Location	InfrastructureProcess	Unit	sugar refinery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				1			
	Unit				unit			
product	sugar refinery	GLO	1	unit	1.00E+00			
resource, land	Transformation, from unknown	-	-	m2	4.17E+4	1	2.35	(4,4,1,5,4,5); Adapted from the dataset 'ethanol fermentation plant'
	Transformation, to industrial area, built up	-	-	m2	2.63E+4	1	2.35	
	Transformation, to industrial area, vegetation	-	-	m2	1.54E+4	1	2.35	
	Occupation, construction site	-	-	m2a	2.08E+5	1	1.90	
	Occupation, industrial area, built up	-	-	m2a	1.31E+6	1	1.90	
	Occupation, industrial area, vegetation	-	-	m2a	7.71E+5	1	1.90	
technosphere	concrete, sole plate and foundation, at plant	CH	0	m3	1.38E+4	1	1.65	
	steel, low-alloyed, at plant	RER	0	kg	1.86E+5	1	1.65	
	steel, converter, unalloyed, at plant	RER	0	kg	4.39E+5	1	1.65	
	chromium steel 18/8, at plant	RER	0	kg	1.61E+5	1	1.65	
	zinc for coating, at regional storage	RER	0	kg	9.56E+4	1	1.65	
	copper, at regional storage	RER	0	kg	4.00E+4	1	1.65	
	nickel, 99.5%, at plant	GLO	0	kg	3.56E+4	1	1.65	
	transport, lorry 28t	CH	0	tkm	1.11E+6	1	2.35	
	transport, freight, rail	RER	0	tkm	5.54E+5	1	2.35	
	diesel, burned in building machine	GLO	0	MJ	1.36E+5	1	1.65	
	electricity, medium voltage, at grid	CH	0	kWh	1.64E+4	1	1.65	
	disposal, building, concrete, not reinforced, to final disposal	CH	0	kg	3.03E+7	1	1.65	
emission air, high population density	Heat, waste	-	-	MJ	5.92E+4	1	1.65	

16.5.3 LCI of ‘Sugar beet, in sugar refinery, CH’

The production of sugar, molasses and pulps from sugar beets is described in detail in paragraph 16.5.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.8 below presents the yields of sugar, molasses and pulps from sugar beets, according to various literature references. The last two rows indicate the average values according to the quoted references and the values used in this study. In the present case, the yields considered correspond to (ZAF 2002) because all the process data is also given by (ZAF 2002) and match the situation in CH. The yields from (Poitrat 1998), for instance, correspond to the situation in FR where the production of molasses is maximised for ethanol production, which is not the case (yet) in CH.

Tab. 16.8 Literature review sugar yields from sugar beet.

Reference	Year	Yields		
		Sugar beet / CH		
		Sugar [kg/t]	Molasses [kg/t]	Pulps [kg/t]
Poitrat 1998	1998	135.3	61.3	257.4
ZAF 2002	2002	156.9	35.9	204.0
ZAF 2005	2005	157.3	30.0	238.1
Average		**149.8**	**42.4**	**233.2**
This study		**156.9**	**35.9**	**204.0**

Unless stated otherwise, the data below is from (ZAF 2002) and given per ton of sugar beet.

Sugar beets are transported from the farm to the sugar refinery over an average distance of 70 km, of which 10 km are done by tractor and 60 km by train.

As far as energy is concerned, the electricity and heat consumed in the process amount to 33 kWh and 297 MJ per ton of sugar beet, distributed over the sugar extraction (9 kWh and 135 MJ), the pressing of pulps (1 kWh), and the purification and crystallisation processes (23 kWh and 162 MJ).

Raw materials used in the process include sulphuric acid (0.063 kg), soda powder (0.345 kg), organic (0.093 kg) and inorganic (0.134) kg chemicals, limestone (29 kg) and hard coal coke (2.5 kg), mostly in the purification process. Average transport distances according to the ecoinvent guidelines are used for the delivery of raw materials to the sugar refinery, including 50 km by 28t lorry and 600 km by train (applicable in the case of Switzerland).

The consumption of water, 94% of which occurs in the washing and diffusion stages, amounts to 1.1 ton per ton of sugar beet. Liquid effluents (incl. water initially in the sugar beet and from washing) amount to 1.740 m^3. Finally, limestone residues (36.6 kg) resulting from the purification process are disposed of in an inert material landfill.

The infrastructure of the sugar refinery is described in the 'sugar refinery' dataset (paragraph 16.5.2), with a sugar production capacity of 200'000 t/yr (i.e. a feed capacity of 1'300 kt/yr of sugar beets) over a lifetime of 50 years, i.e. 1.57E-8 unit per ton of sugar beets.

Carbon dioxide input and emissions (65.2 kg) are considered to satisfy the carbon balance amongst the various products in spite of the economic allocation. Indeed, because the economic allocation is applied, sugar (through sugar beet) benefits from a CO_2 credit which is larger than its actual carbon content (allocation of 91.7% of the sugar beet to sugar). In order to satisfy the carbon balance between the three outputs (sugar, molasses and pulps), a (fictive) CO_2 output of 65.2 kg per ton of sugar beet is taken into account and allocated to sugar. In order to balance CO_2 emissions, a (ficitve) CO_2 input (as resource, from air) of the same amount (65.2 kg/t) is also included and allocated to pulps and molasses, according to their respective carbon content. The same approach is applied throughout the chapter in order to allocate the correct carbon credit to each product in multi-output (MO) processes, according to its actual carbon content.

Waste heat to air (133 MJ) is calculated to close the energy balance.

The three outputs of the MO-process 'sugar beet, in sugar refinery' include:

- sugar, from sugar beet, at sugar refinery: **156.9 kg/t sugar beets**;
- molasses, from sugar beet, at sugar refinery: **35.9 kg/t sugar beets**;
- pulps, from sugar beet, at sugar refinery: **204.0 kg/t sugar beets**.

The economic allocation approach (paragraph 16.5, Tab. 16.5) is used, with allocation factors of 93.0%, 4.7% and 2.3% respectively (applicable to common stages including the feedstock). The unit process raw data is indicated in Tab. 16.9.

Tab. 16.9 Unit process raw data of the dataset 'sugar beet, in sugar refinery', CH.

	Name	Location	InfrastructureProcess	Unit	sugar beet, in sugar refinery	sugar, from sugar beet, at sugar refinery	molasses, from sugar beet, at sugar refinery	pulps, from sugar beet, at sugar refinery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	sugar, from sugar beet, at sugar refinery	CH	0	kg	1.57E-01	100.0					
product	molasses, from sugar beet, at sugar refinery	CH	0	kg	3.59E-02		100.0				
product	pulps, from sugar beet, at sugar refinery	CH	0	kg	2.04E-01			100.0			
resource, in air	Carbon dioxide, in air	-	-	kg	6.52E-2	0.0	29.2	70.8	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	sugar beets IP, at farm	CH	0	kg	1.00E+0	91.7	4.5	3.8	1	1.21	(1,1,1,1,1,5); Environmental report of Swiss sugar manufacturer
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	2.97E-1	93.7	4.6	1.7	1	1.21	
	electricity, medium voltage, at grid	CH	0	kWh	3.33E-2	90.1	4.3	5.6	1	1.21	
	tap water, at user	CH	0	kg	1.10E+0	92.0	4.5	3.5	1	1.21	
	sulphuric acid, liquid, at plant	RER	0	kg	6.31E-5	95.3	4.7	0.0	1	1.21	
	soda, powder, at plant	RER	0	kg	3.45E-4	95.3	4.7	0.0	1	1.21	
	chemicals organic, at plant	GLO	0	kg	9.29E-5	95.3	4.7	0.0	1	1.21	
	chemicals inorganic, at plant	GLO	0	kg	1.34E-4	95.3	4.7	0.0	1	1.21	
	limestone, milled, loose, at plant	CH	0	kg	2.90E-2	95.3	4.7	0.0	1	1.21	
	hard coal coke, at plant	RER	0	MJ	2.51E-3	95.3	4.7	0.0	1	1.21	
	transport, freight, rail	CH	0	tkm	7.94E-2	92.6	4.5	2.9	1	2.05	
	transport, lorry 28t	CH	0	tkm	1.62E-3	95.3	4.7	0.0	1	2.05	
	transport, tractor and trailer	CH	0	tkm	1.00E-2	91.7	4.5	3.8	1	2.05	
	sugar refinery	GLO	1	unit	1.57E-11	88.2	4.2	7.6	1	3.05	
	disposal, limestone residue, 5% water, to inert material landfill	CH	0	kg	3.66E-2	91.7	4.5	3.8	1	1.21	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.74E-3	93.8	4.6	1.6	1	1.21	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	6.60E-2	100.0	0.0	0.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.33E-1	90.1	4.3	5.6	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

16.5.4 LCI of 'Molasses, from sugar beet, in distillery, CH'

The production of ethanol and syrup from sugar beet molasses is described in detail in paragraph 16.5.1. This paragraph describes the actual life cycle inventory of the process as defined in this study.

The data in Tab. 16.10 below presents the yields of anhydrous ethanol (99.7% wt.) and syrup from sugar beet molasses, according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

In the present case, the yields considered correspond to the process described in the etha+ project of Alcosuisse (ENERS 2005) because all of the process data is also given by (ENERS 2005), an update of (INTERIS 2002) and (LASEN 2004b), and match the situation in CH.

Tab. 16.10 Literature review ethanol yields from sugar beet molasses.

Reference	**Year**	**Yields**	
		Molasses / CH	
		Ethanol 99.7% wt. [kg/t]	Syrup [kg/t]
Woods 2000	2000	159.0	
INTERIS 2002	2002	245.3	614.3
van Vaals & Braks 2003	2003	219.9	
LASEN 2004b	2004	245.3	614.5
ENERS 2005	2005	246.1	614.3
Average		**223.1**	**614.4**
This study (ethanol 99.7% wt. wet basis)		**246.1**	**614.3**
This study (ethanol 95% wt. wet basis)		**258.2**	**614.3**
This study (ethanol 95% wt. dry basis)		**245.3**	**614.3**

The significant difference between the yield given by (Woods 2000) and the other references is mainly explained by a different composition of the molasses (sugar and water content).

Unless stated otherwise, the data below is from (ENERS 2005) and given per ton of molasses.

Sugar beet molasses are transported to the distillery over an average distance of 70 km by train.

As far as energy is concerned, the electricity and heat consumed in the process amount to 57.0 kWh and 3’104 MJ per ton of molasses, distributed over the stages of fermentation and distillation (14.4 kWh and 976 MJ) and stillage treatment (42.6 kWh and 2’128 MJ).

Raw materials used in the process include sulphuric acid (9.3 kg), as well as nitrogen-based nutrients in the form of ammonium sulphate (1.23 kg N) and diammonium phosphate (1.85 kg N). Average transport distances according to the ecoinvent guidelines are used for the delivery of raw materials, including 50 km by 28t lorry and 600 km by train.

The consumption of water (dilution of the feedstock prior to fermentation) amounts to 1.980 ton per ton of molasses. Liquid effluents (incl. flegmasses from the distillation stage and wastewater from stillage treatment) amount to 1.870 m^3.

The infrastructure of the ethanol distillery is described in the ‘ethanol fermentation plant’ dataset, with a production capacity of 90’000 t/yr (i.e. a feed capacity of 370 kt/yr of sugar beet molasses) over a lifetime of 20 years. According to the respective investment costs of the various process units, it is assumed that dehydration accounts for 12.5% of the total infrastructure and therefore, the actual infrastructure input is 1.20E-7 unit per ton of molasses.

Direct carbon dioxide (CO_2) emissions from the fermentation process amount to 250 kg (i.e. 0.972 kg per kg of hydrated ethanol or 1.020 kg per kg of anhydrous ethanol). A correction of 161 kg (input and output) is applied to satisfy the carbon balance (based on the carbon content) between ethanol and the syrup in spite of the economic allocation. Waste heat to air (205 MJ) is calculated to close the energy balance.

The two outputs of the MO-process ‘sugar beet molasses, in distillery’ include:

- ethanol, 95% in H2O, from sugar beet molasses, at distillery (dry basis): **245.3 kg/t molasses**;
- syrup, from sugar beet molasses, at distillery: **614.3 kg/t molasses**.

The economic allocation approach (paragraph 16.5, Tab. 16.6) is used, with factors for common stages (including the feedstock) of 94.5% and 5.5% respectively. The unit process raw data is indicated in Tab. 16.11.

Tab. 16.11 Unit process raw data of the dataset ‘sugar beet molasses, in distillery’, CH.

	Name	Location	InfrastructureProcess	Unit	molasses, from sugar beet, in distillery	ethanol, 95% in H2O, from sugar beet molasses, at distillery	syrup, from sugar beet molasses, at distillery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	ethanol, 95% in H2O, from sugar beet molasses, at distillery	CH	0	kg	2.45E-01	100.0				
product	syrup, from sugar beet molasses, at distillery	CH	0	kg	6.14E-01		100.0			
resource, in air	Carbon dioxide, in air	-	-	kg	1.61E-1	0.0	100.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	molasses, from sugar beet, at sugar refinery	CH	0	kg	1.00E+0	94.5	5.5	1	1.21	(1,2,1,1,1,5); etha+ project Alcosuisse, industrial data
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	3.10E+0	23.9	76.1	1	1.21	
	electricity, medium voltage, at grid	CH	0	kWh	5.70E-2	94.5	5.5	1	1.21	
	tap water, at user	CH	0	kg	1.98E+0	94.5	5.5	1	1.21	
	sulphuric acid, liquid, at plant	RER	0	kg	9.26E-3	94.5	5.5	1	1.21	
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	1.23E-3	94.5	5.5	1	1.21	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	1.85E-3	94.5	5.5	1	1.21	
	transport, freight, rail	CH	0	tkm	7.74E-2	94.5	5.5	1	2.05	
	transport, lorry 28t	CH	0	tkm	6.18E-4	94.5	5.5	1	2.05	
	ethanol fermentation plant	CH	1	unit	1.20E-10	41.2	58.8	1	3.05	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.87E-3	14.4	85.6	1	1.21	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	4.11E-1	100.0	0.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	2.25E-1	94.5	5.5	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

16.6 Ethanol from potatoes, CH

16.6.1 System characterization

The system described in this paragraph includes the production of hydrated ethanol and DDGS[38] from potatoes in the Swiss context (Fig. 16.5). The dehydration to ethanol 99.7% wt. is described in chapter 14.9.

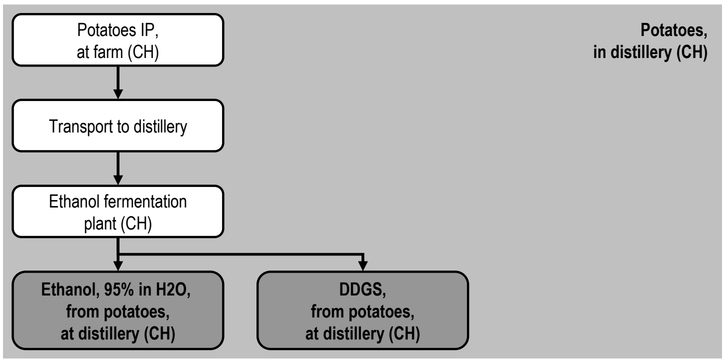

Fig. 16.5 Ethanol from potatoes, CH: system definition and boundaries.

Like in the case of ethanol from sugar beet molasses, the description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse (ENERS 2005; INTERIS 2002) and the ASIATIC project (LASEN 2004a). The ethanol plant considered in this case processes 500 kt/yr of potatoes, and produces approx. 36 kt/yr of hydrated ethanol (95% wt.) as well as 54 kt/yr of DDGS (90% wt. dry matter).

The reception and washing stages of potatoes are quite similar to those for sugar beets. Upon arrival to the plant, the potatoes are unloaded with large water hoses and either stored into silos or dumped directly into wet hoppers. After removal of rocks, mud or sand trash, potatoes are washed and then fed to the grating unit, to make some kind of potato pulp or mash.

The liquefaction and saccharification unit aims at converting the potato mash into a fermentable pulp, by hydrolysis of the starch contained in the mash. The proposed process is an enzymatic hydrolysis. The enzymes indeed break the glucidic bonds of the starch macromolecule to get fermentable sugars. The liquefaction/saccharification line operates in a continuous mode and comprises (1) the conversion of the mash into a pastry at 45°C, (2) the liquefaction stage (2 hours at 90°C in several tanks), and (3) the saccharification stage (about 15 hours at 60°C again in several tanks). The latter is a slow process and continues even in the fermentation stage, which follows the saccharification stage (Fig. 16.6).

The fermentation and distillation units are similar to those described in the production of ethanol from sugar beet molasses (paragraph 16.5) and therefore are not described again. The reader is advised to refer to the corresponding paragraph for further details.

The separation unit mainly aims at separating insoluble dry matter (often referred to as the distiller's wash) from the soluble one contained in the stillage. This stage also allows, firstly, to increase the quantities of stillage recycled in the fermentation stage while at the same time reducing the amount of dry matter (clarified stillage) and secondly, to reduce the energy consumption and investment costs of the drying unit. Separation is performed by means of settling tanks (clarifiers) coupled with centrifuges producing two distinct outputs: (1) the distiller’s wash, where 40% of the total dry matter of the stillage remain (with a concentration of about 30% DM), and (2) the clarified stillage (with a dry matter concentration below 10%). The distiller's wash is sent to the drying unit, while the clarified stillage goes to the pre-concentration unit for further treatment (with a fraction being recycled to the fermentation unit in order to reduce both the consumption of water and the dimensions of the stillage treatment units, i.e. the pre-concentration and the concentration units).

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[38] DDGS. Distiller’s dried grains with solubles.

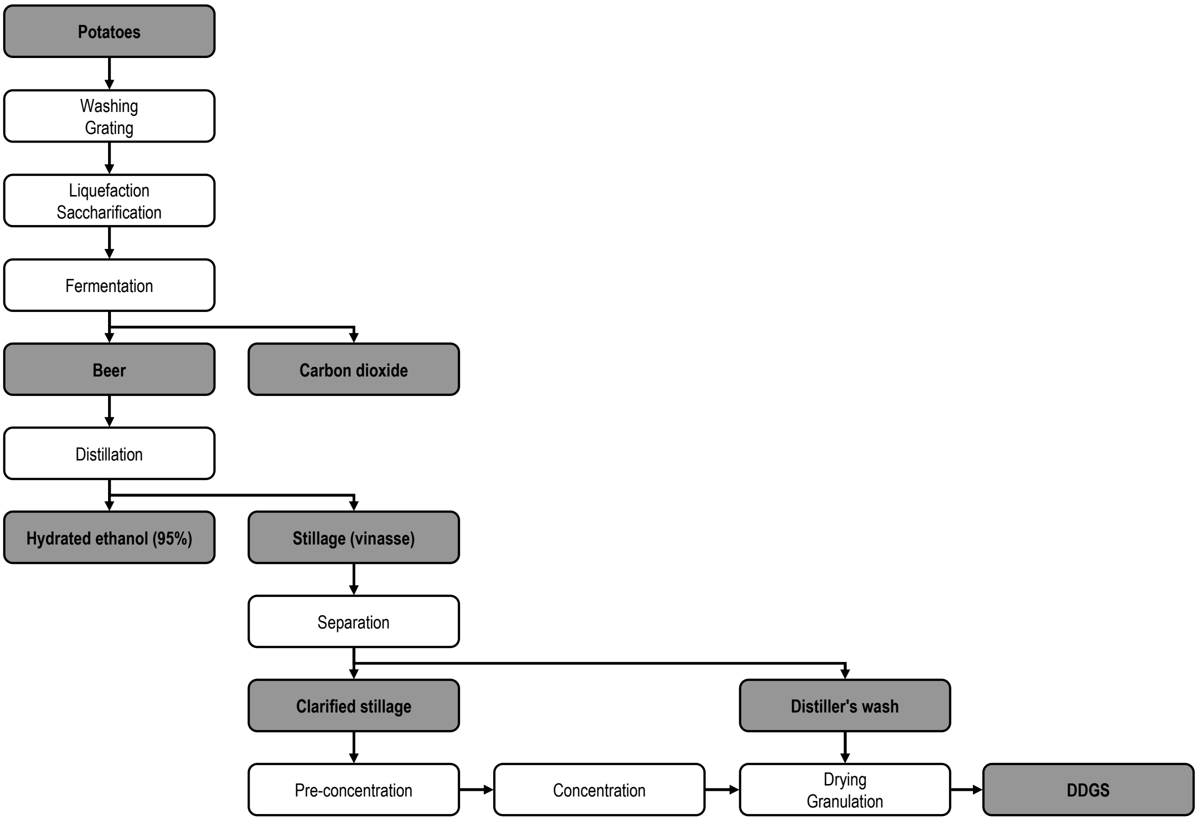


Fig. 16.6 Production stages for the processing or potatoes to hydrated ethanol and DDGS.

Although the dry matter content of the various intermediate products may vary from one feedstock to another due to the initial composition, the pre-concentration and concentration stages, again, are identical to those described in the production of ethanol from sugar beet molasses (paragraph 16.5) and thus are not described again.

The drying and granulation unit aims at drying the distiller's wash together with the syrup (leaving the concentration stage) to obtain DDGS at 90% DM in the form of granules, used as animal feed. Although the term DDGS usually refers to the product resulting from the corn-to-ethanol process, the same term is used here, by analogy. The syrup coming out of the pre-concentration unit is mixed with the distiller's wash coming from the separation unit and dried in a direct heating drum drier operated with natural gas. The produce coming out of the drier is evacuated by pneumatic transport towards cyclones. The evaporated water vapour is washed to comply with air emission standards. The dry product falls in a granulating press, and goes through an air cooler. Cold pellets are taken on an elevator towards a sieve and fines are recycled to the mixer, upstream from the drier. Pellets with the required size are stored before distribution.

According to the data from Tab. 16.13 and more specifically from (ENERS 2005; INTERIS 2002), 1 ton of potatoes (14% starch, 78% water) results in:

- 69.1 kg of hydrated ethanol (95% wt., dry basis);
- 107.9 kg of DDGS (90% dry matter, 10% water).

Allocation between ethanol and DDGS is performed, based on the estimated market prices (ENERS 2005) of anhydrous ethanol (i.e. 1.40 CHF/l) and potatoes DDGS (i.e. 240 CHF/t) in Switzerland. The resulting allocation factors are indicated for each group of process stages in Tab. 16.12.

Tab. 16.12 Allocation factors in the production of ethanol from potatoes (CH).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Saccharification Fermentation Distillation	Hydrated ethanol	95.6%	45.6%	12.7%	49.0%
	DDGS	4.4%	54.4%	87.3%	51.0%
Stillage treatment	Hydrated ethanol	0.0%	0.0%	0.0%	0.0%
	DDGS	100.0%	100.0%	100.0%	100.0%

16.6.2 LCI of ‘Potatoes, in distillery, CH’

The production of ethanol and DDGS from potatoes is described in detail in paragraph 16.6.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.13 presents the yields of anhydrous ethanol (99.7% wt.) and DDGS from potatoes, according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

In the present case, the ethanol yield considered corresponds to the performance of the process described in the etha+ project of Alcosuisse (ENERS 2005). The yield of DDGS, however, is adapted to the composition of potatoes in the ecoinvent database (15% starch, 7% non-sugars, 78% water), and coïncidentally corresponds to the average of (LASEN 2004b) and (ENERS 2005).

Tab. 16.13 Literature review ethanol yields from potatoes.

Reference	Year	Yields	
		Potatoes / CH	
		Ethanol 99.7% wt. [kg/t]	DDGS [kg/t]
INTERIS 2002	2002	69.1	
Mehlin et al. 2003	2003	72.4	
van Vaals & Braks 2003	2003	56.5	
LASEN 2004b	2004	74.2	130.1
ENERS 2005	2005	69.3	85.7
Average		**68.3**	**107.9**
This study (ethanol 99.7% wt. wet basis)		**69.3**	**107.9**
This study (ethanol 95% wt. wet basis)		**72.7**	**107.9**
This study (ethanol 95% wt. dry basis)		**69.1**	**107.9**

Unless stated otherwise, the data below is from (ENERS 2005) and given per ton of fresh potatoes.

Potatoes are transported to the distillery over an average distance of 70 km, of which 10 km are done by tractor and 60 km by train. Only potatoes IP are considered as an input because of economics.

As far as energy is concerned, the electricity and heat consumed in the process amount to 39.4 kWh and 1’072 MJ per ton of potatoes, distributed over the stages of pretreatment and saccharification (8.5 kWh and 77 MJ), fermentation and distillation (4.7 kWh and 365 MJ) and stillage treatment (26.2 kWh and 630 MJ). Some additional natural gas (244 MJ) is burned in the drying of DDGS (before the granulation process).

Raw materials used in the process include sulphuric acid (1.30 kg), soda powder (3.01 kg), and N-based nutrients in the form of ammonium sulphate (0.79 kg N) and diammonium phosphate (0.79 kg N). The transport distances for the delivery of raw materials include 50 km by 28t lorry and 600 km by train, based on the ecoinvent guidelines.

The consumption of water amounts to 74 kg per ton of potatoes. Liquid effluents (incl. flegmasses from the distillation stage and wastewater from stillage treatment) amount to 0.780 m^3. Most of the water in the effluents comes from the initial water in the feedstock.

The infrastructure of the ethanol distillery is described in the 'ethanol fermentation plant' dataset, with a production capacity of 90'000 t/yr (i.e. a feed capacity of 1'300 kt/yr of potatoes) over a lifetime of 20 years. The actual infrastructure input (excluding the dehydration stage) is 3.54E-8 unit per ton of fresh potatoes.

Direct carbon dioxide (CO_2) emissions from the fermentation process amount to 71 kg (i.e. 0.972 kg per kg of hydrated ethanol or 1.020 kg per kg of anhydrous ethanol), with a total of 98 kg. A correction of 122 kg (input and output) is applied to satisfy the carbon balance (based on the carbon content) between ethanol and DDGS in spite of the economic allocation. Finally, waste heat to air (411 MJ) is calculated to close the energy balance.

The two outputs of the MO-process 'potatoes, in distillery' include:

- ethanol, 95% in H2O, from potatoes, at distillery (dry basis): **69.1 kg/t potatoes**;
- DDGS, from potatoes, at distillery: **107.9 kg/t potatoes**.

The economic allocation approach (paragraph 16.6, Tab. 16.12) is used, with factors for common stages (including the feedstock) of 95.6% and 4.4% respectively. The unit process raw data is indicated in Tab. 16.14.

Tab. 16.14 Unit process raw data of the dataset 'potatoes, in distillery', CH.

	Name	Location	InfrastructureProcess	Unit	potatoes, in distillery	ethanol, 95% in H2O, from potatoes, at distillery	DDGS, from potatoes, at distillery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	ethanol, 95% in H2O, from potatoes, at distillery	CH	0	kg	6.91E-02	100.0				
product	DDGS, from potatoes, at distillery	CH	0	kg	1.08E-01		100.0			
resource, in air	Carbon dioxide, in air	-	-	kg	1.22E-1	0.0	100.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	potatoes IP, at farm	CH	0	kg	1.00E+0	95.6	4.4	1	1.21	(1,2,1,1,1,5); etha+ project Alcosuisse, industrial data
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.44E-1	0.0	100.0	1	1.21	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	1.07E+0	39.4	60.6	1	1.21	
	electricity, medium voltage, at grid	CH	0	kWh	3.94E-2	32.0	68.0	1	1.21	
	tap water, at user	CH	0	kg	7.40E-2	95.6	4.4	1	1.21	
	sulphuric acid, liquid, at plant	RER	0	kg	1.30E-3	95.6	4.4	1	1.21	
	soda, powder, at plant	RER	0	kg	3.01E-3	95.6	4.4	1	1.21	
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	7.88E-4	95.6	4.4	1	1.21	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	7.88E-4	95.6	4.4	1	1.21	
	transport, freight, rail	CH	0	tkm	6.37E-2	95.6	4.4	1	2.05	
	transport, lorry 28t	CH	0	tkm	3.12E-4	95.6	4.4	1	2.05	
	transport, tractor and trailer	CH	0	tkm	1.00E-2	95.6	4.4	1	2.05	
	ethanol fermentation plant	CH	1	unit	3.54E-11	40.8	59.2	1	3.05	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	7.80E-4	12.7	87.3	1	1.21	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.20E-1	100.0	0.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	4.11E-1	32.0	68.0	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

16.7 Ethanol from wood, CH

16.7.1 System characterization

The system described in this paragraph includes the production of hydrated ethanol and electricity from wood chips (Fig. 16.7). The dehydration to ethanol 99.7% wt. is described in chapter 14.9.

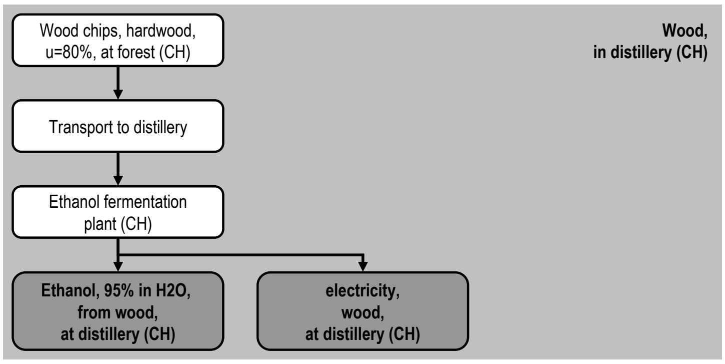


Fig. 16.7 Ethanol from wood, CH: system definition and boundaries.

The description of the production process as well as LCI data of this process are adapted from various references including (LASEN 2002; Gnansounou et al. 2005; LASEN 2002; LASEN 2004a; Wooley et al. 1999; Aden et al. 2002). The ethanol plant considered in this case processes 275 kt/yr of wood chips, and produces 42 kt/yr of hydrated ethanol (95% wt.) as well as 1'800 MWh/yr of electricity (net production).

In this study, the conversion of wood chips to ethanol is based on enzymatic hydrolysis of cellulose and co-fermentation of glucose and xylose to ethanol (Wooley et al. 1999). This choice is driven by two considerations. Firstly, state-of-the-art technology can achieve competitive costs through the use of enzymes (Wyman 2001). Secondly, enzymes appear to offer the greatest prospects for continued improvements (Lynd et al. 1996). The National Renewable Energy Laboratory (NREL) has documented extensive performance and cost information (Wooley et al. 1999), and even though other performance and designs are feasible, the NREL information provides a convenient platform from which to evaluate enzymatic routes. The technology described here (Fig. 16.8) is based on that configuration.

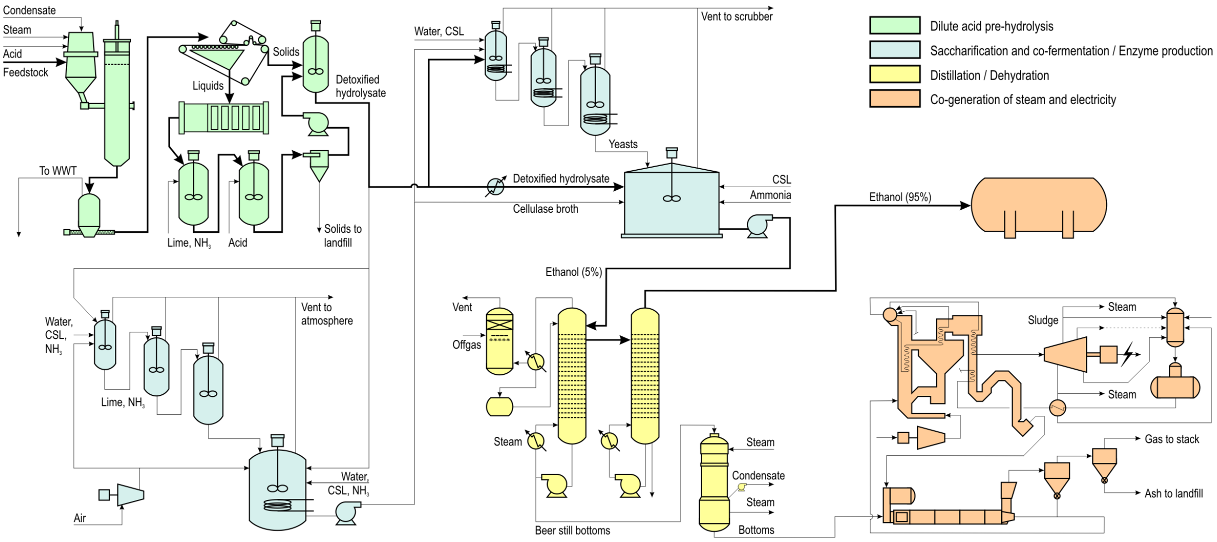


Fig. 16.8 Process design of the conversion of wood chips to ethanol.

Because the overall enzymatic route is well described elsewhere, the reader is referred to these sources for more detailed information (Wooley et al. 1999; Wyman 2001; Knauf et al. 2004). In more general terms, the process begins with the pre-treatment step in which the material is held for around 10 minutes at about 160-190°C with 0.5-1.0% dilute sulphuric acid to catalyze hemicellulose removal by hydrolysis and expose the cellulose for saccharification by enzymes with high yields. Acid hydrolysis of hemicellulose realizes good yields of sugars from hemicellulose during pre-treatment, and acid costs are relatively low. During this operation, the sugars in hemicellulose are released, together with other constituents in wood chips such as acetic acid. The pre-treated material then passes to a vessel with a sudden drop in pressure to rapidly lower the temperature and stop the reaction. This flash operation also removes some of the acetic acid, furfural, and other fermentation inhibitors that are either released from the biomass or produced by degradation reactions during pre-treatment. Next, the liquid is removed from the remaining solid fraction that contains most of the cellulose and lignin and pumped to an ion exchange operation to remove a portion of acetic and virtually all of the sulphuric acid. The liquid is neutralized with lime, and additional lime is added to increase the pH to about 10 to remove toxics to downstream biological steps in an operation known as “overliming” (Fig. 16.8). The treated liquid is then mixed back with the solids before the fermentation.

A small portion of the solids and the treated liquid is fed to a batch operation to produce cellulase enzyme by the fungus Trichoderma reesei, and the entire effluent from cellulase production plus the bulk of the pre-treated solids not used for making enzymes are added to a fermentor to release glucose from cellulose. In addition, the conditioned liquid hydrolyzate is also added to the same vessel along with an organism that ferments the sugars from hemicellulose plus the glucose released from cellulose to ethanol. In this operation, referred to as SSCF (simultaneous saccharification and co-fermentation), the glucose released from cellulose during enzymatic hydrolysis is quickly converted to ethanol.

The fermented beer containing about 5% (vol.) ethanol passes on to distillation where it is concentrated to approximately 95% ethanol in the overhead. The solids, containing mostly lignin and solubles from distillation are concentrated and burned to generate steam that can provide all of the heat and electricity for the process with some excess electricity left to export. Water is treated by anaerobic digestion, and the resulting biogas is burned for steam generation.

According to the data from Tab. 16.16, 1 ton of wood chips (45% water, u=80%) results in:

- 144.1 kg of hydrated ethanol (95% wt., dry basis);
- 6.5 kWh of electricity (net production).

Allocation between ethanol and electricity is performed, based on estimated market prices (ENERS 2005) of anhydrous ethanol (i.e. 1.40 CHF/l) and electricity (i.e. 0.10 CHF/kWh) in Switzerland. The resulting allocation factors are indicated in Tab. 16.15.

Tab. 16.15 Allocation factors in the production of ethanol from wood chips (CH).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Pre-treatment SSCF	Hydrated ethanol	99.7%	99.4%	-	100.0%
Ethanol recovery	Electricity	0.3%	0.6%	-	0.0%

16.7.2 LCI of ‘Wood, in distillery, CH’

The production of ethanol and electricity from wood chips is described in detail in paragraph 16.7.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.16 presents the yields of anhydrous ethanol (99.7% wt.) and excess electricity from wood (more generally lignocellulosic biomass), according to various literature references. In each case, the yield (often given on a dry matter feedstock basis in the literature) is adapted to match the water content of the feed considered here (i.e. wood chips, hardwood, u=80%, at forest). The yields, therefore, are given in kg anhydrous ethanol (99.7%) per ton of wood chips (wet basis, water content 44%). The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

The ethanol yield considered here corresponds to the average value according to the quoted references. The same yield is actually obtained with the technology described in (Wooley et al. 1999), but with the updated conversion efficiencies given in (Aden et al. 2002).

Differences between the various references can be explained by:

- the conversion efficiencies considered (cellulose to glucose, glucose to ethanol, xylan to xylose, xylose to ethanol, etc.);
- the composition (incl. water content) of the feedstock (influenced by the type and nature of the feedstock);
- the technology (more specifically, the hydrolysis and fermentation stages);
- the type of enzymes (commercial enzymes or produced on-site from a fraction of the pretreated feedstock);
- the nature and performance of the yeasts in the fermentation stage (conversion of only primary sugars or both primary and secondary sugars such as mannose, galactose, arabinose, etc.).

It is worth noting that the references listed in Tab. 16.16 are not exclusively limited to woody biomass, and cover a larger scope of lignocellulosic feedstocks (incl. straw and other agricultural residues).

Tab. 16.16 Literature review ethanol yields from wood (lignocellulosic biomass).

Reference	Year	Yields
		Wood (lignocellulosic biomass) / CH Ethanol 99.7% wt. [kg/t]
ARKENOL 1999	1999	210.6
Wooley et al. 1999	1999	116.0
Graf & Koehler 2000	2000	89.9
Graf & Koehler 2000	2000	114.4
Aden et al. 2002	2002	162.9
LASEN 2002	2002	124.9
Reith et al. 2002	2002	140.0
Reynolds 2002	2002	146.2
NOVEM 2003	2003	139.1
Bullard et al. 2003	2003	154.2
Hamelinck et al. 2003	2003	121.9
Woods & Bauen 2003	2003	129.3
IEA 2004	2004	177.8
Lynd & Wang 2004	2004	146.7
Sheehan et al. 2004	2004	148.6
Pimentel & Patzek 2005	2005	174.9
VIEWLS 2005	2005	165.0
ETEK 2006	2006	109.3
IOGEN 2006	2006	168.9
Average		**144.5**
This study (ethanol 99.7% wt. wet basis)		**144.5**
This study (ethanol 95% wt. wet basis)		**151.7**
This study (ethanol 95% wt. dry basis)		**144.1**

Unless stated otherwise, the data below is from (Wooley et al. 1999) and is given per ton of wood chips (i.e. 555.5 kg dry matter), on a wet basis (see Fig. 16.9).

Wood chips
(u=80%, hardwood)

Composition (% wt. dry matter basis):

Cellulose	42.7%
Hemicellulose	28.7%
Xylan	19.1%
Arabinan	0.8%
Mannan	3.8%
Galactan	0.2%
Acetate	4.6%
Lignin	27.7%
Ash	1.0%

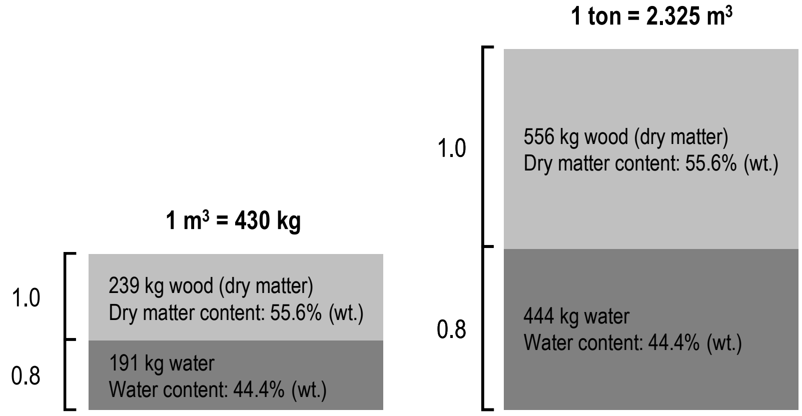


Fig. 16.9 Characteristics of wood chips (hardwood, U=80%).

Wood chips are transported to the distillery from nearby forest areas over an average distance of 70 km, of which 5 km are done by tractor and trailer and 65 km by 28t lorry.

As far as energy is concerned, the respective consumptions of electricity and heat amount to 163.9 kWh and 1'983 MJ per ton of chips, distributed over the stages of pre-hydrolysis (13.5 kWh and 987 MJ), enzyme production (104.2 kWh), simultaneous sacchirification and co-fermentation (18.2 kWh), distillation (3.1 kWh and 996 MJ), and utilities incl. wastewater treatment (24.9 kWh). Some additional natural gas (244 MJ) is burned in the drying of DDGS (before the granulation process). All the heat and power are produced locally by burning unconverted solids such as lignin. Some excess electricity is also produced as a by-product of ethanol, which amounts to 6.5 kWh per ton of wood chips.

Raw materials used in the process include sulphuric acid (11.9 kg), lime (4.6 kg), and organic chemicals (0.02 kg). Nutrients for bacterial growth are in the form of ammonia (9.5 kg), diammonium phosphate (0.241 kg N), ammonium sulphate (0.171 kg N), calcium chloride (0.173 kg) and magnesium sulphate (0.078 kg). The transport distances for the delivery of raw materials include 50 km by 28t lorry and 600 km by train, based on the ecoinvent guidelines.

The consumption of water amounts to 1'160 kg per ton of chips. The treatment of all liquid effluents is performed on site, in an integrated wastewater treatment plant, and is included in the present inventory. Finally, the gypsum (15.7 kg) resulting from overliming in the pre-hydrolysis stage is disposed of in a landfill.

The infrastructure of the ethanol distillery is described in the 'ethanol fermentation plant' dataset, with a production capacity of 90'000 t/yr (i.e. a feed capacity of 623 kt/yr of wood chips) over a lifetime of 20 years. The actual infrastructure input (excluding dehydration) is 5.96E-8 unit per ton of chips.

Direct emissions of the wood-to-ethanol process include carbon dioxide emissions from the fermentation process (165 kg, i.e. 1.088 kg per kg of hydrated ethanol or 1.142 kg per kg of anhydrous ethanol), and emissions from the combustion of unconverted solids. Here, the process 'wood chips, burned in cogen 6400kWth, emission control' is adapted and used to model the combustion. The properties of unconverted solids are given in Tab. 16.17 and compared with wood chips (u=40%).

Tab. 16.17 Characteristics and properties of unconverted solids, compared with wood chips (u=40%).

	Unconverted solids		Wood chips, u=40%	
Water content	54.9	% w/w	28.6	% w/w
Dry matter content	45.1	% w/w	71.4	% w/w
Carbon content (dry matter basis)	53.5	% w/w	49.4	% w/w
Higher heating value	21.8	MJ/kg	20.2	MJ/kg
Lower heating value	9.8	MJ/kg	14.4	MJ/kg
Dry matter input	0.451	kg/kg	0.714	kg/kg
Carbon input	0.241	kg/kg	0.353	kg/kg
Energy input	9.830	MJ/kg	14.400	MJ/kg
Heat production	5.918	MJ/kg	11.045	MJ/kg
Electricity production	0.363	kWh/kg	0.331	kWh/kg

The process ‘wood chips, burned in cogen 6400kWth, emission control’ is adapted according to the following rules:

- all inputs from the technosphere are considered to be proportional to the dry matter input;
- emissions of hydrocarbons are proportional to the carbon input (see Tab. 16.17);
- emissions of waste heat are proportional to the energy input (see Tab. 16.17);
- all other emissions are proportional to the dry matter input (see Tab. 16.17).

The two outputs of the MO-process ‘wood, in distillery’ include:

- ethanol, 95% in H2O, from wood, at distillery (dry basis): **144.1 kg/t wood chips**;
- electricity, wood, at distillery: **6.5 kWh/t wood chips**.

The economic allocation approach (paragraph 16.7, Tab. 16.15) is used, with allocation factors of 99.7% and 0.3% respectively (applicable to common stages including the feedstock). The unit process raw data is indicated in Tab. 16.18.

Tab. 16.18 Unit process raw data of the dataset ‘wood, in distillery’, CH.

	Name	Location	InfrastructureProcess	Unit	wood, in distillery	ethanol, 95% in H2O, from wood, at distillery	electricity, wood, at distillery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kWh			
product	ethanol, 95% in H2O, from wood, at distillery	CH	0	kg	1.44E-01	100.0				
product	electricity, wood, at distillery	CH	0	kWh	6.49E-03		100.0			
technosphere	wood chips, hardwood, u=80%, at forest	RER	0	m3	2.32E-3	99.7	0.3	1	1.22	(2,3,1,2,1,5); etha+ project Alcosuisse, SSCF technology from NREL
	tap water, at user	CH	0	kg	1.16E+0	99.7	0.3	1	1.22	
	sulphuric acid, liquid, at plant	RER	0	kg	1.19E-2	99.7	0.3	1	1.22	
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	1.71E-4	99.7	0.3	1	1.22	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	2.41E-4	99.7	0.3	1	1.22	
	quicklime, in pieces, loose, at plant	CH	0	kg	4.64E-3	99.7	0.3	1	1.22	
	ammonia, liquid, at regional storehouse	CH	0	kg	9.52E-3	99.7	0.3	1	1.22	
	maize starch, at plant	DE	0	kg	3.81E-3	99.7	0.3	1	1.22	
	magnesium sulphate, at plant	RER	0	kg	7.85E-5	99.7	0.3	1	1.22	
	calcium chloride, CaCl2, at regional storage	CH	0	kg	1.73E-4	99.7	0.3	1	1.22	
	chemicals organic, at plant	GLO	0	kg	3.45E-5	99.7	0.3	1	1.22	
	transport, freight, rail	CH	0	tkm	1.92E-2	99.7	0.3	1	2.05	
	transport, lorry 28t	CH	0	tkm	6.66E-2	99.7	0.3	1	2.05	
	transport, tractor and trailer	CH	0	tkm	5.00E-3	99.7	0.3	1	2.05	
	ethanol fermentation plant	CH	1	unit	5.96E-11	99.7	0.3	1	3.05	
	disposal, gypsum, 19.4% water, to inert material landfill	CH	0	kg	1.57E-2	99.7	0.3	1	1.22	
	chlorine, liquid, production mix, at plant	RER	0	kg	8.39E-7	99.7	0.3	1	1.32	(4,4,2,1,1,5); adapted from the dataset 'wood chips, in cogen 6400kWth, wood, emission control', according to actual water, carbon and energy content of the fuel (unconverted solids, mainly lignin)
	sodium chloride, powder, at plant	RER	0	kg	1.05E-5	99.7	0.3	1	1.32	
	lubricating oil, at plant	RER	0	kg	8.39E-6	99.7	0.3	1	1.32	
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	8.39E-6	99.7	0.3	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to landfarming	CH	0	kg	3.38E-4	99.7	0.3	1	1.32	
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	8.39E-6	99.7	0.3	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	3.38E-4	99.7	0.3	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	6.78E-4	99.7	0.3	1	1.32	
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	2.01E-6	99.7	0.3	1	1.32	
	water, decarbonised, at plant	RER	0	kg	2.01E-3	99.7	0.3	1	1.32	
	urea, as N, at regional storehouse	RER	0	kg	6.86E-5	99.7	0.3	1	1.32	
	cogen unit 6400kWth, wood burning, building	CH	1	unit	6.19E-10	99.7	0.3	1	3.10	
	cogen unit 6400kWth, wood burning, common components for	CH	1	unit	2.48E-9	99.7	0.3	1	3.10	
	cogen unit 6400kWth, wood burning, components for electricity only	CH	1	unit	2.48E-9	99.7	0.3	1	3.10	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	7.43E-1	99.6	0.4	1	1.05	(1,1,1,1,1,1); calculation, to close carbon balance
	Heat, waste	-	-	MJ	2.91E+0	99.7	0.3	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Acetaldehyde	-	-	kg	1.56E-7	99.7	0.3	1	1.63	(4,4,2,1,1,5); adapted from the dataset 'wood chips, in cogen 6400kWth, wood, emission control', according to actual water, carbon and energy content of the fuel (unconverted solids, mainly lignin)
	Ammonia	-	-	kg	4.35E-5	99.7	0.3	1	1.39	
	Arsenic	-	-	kg	2.56E-9	99.7	0.3	1	5.12	
	Benzene	-	-	kg	2.52E-6	99.7	0.3	1	1.63	
	Benzene, ethyl-	-	-	kg	8.32E-8	99.7	0.3	1	1.63	
	Benzene, hexachloro-	-	-	kg	2.00E-14	99.7	0.3	1	3.10	
	Benzo(a)pyrene	-	-	kg	1.39E-9	99.7	0.3	1	3.10	
	Bromine	-	-	kg	1.54E-7	99.7	0.3	1	5.12	
	Cadmium	-	-	kg	1.79E-9	99.7	0.3	1	5.12	
	Calcium	-	-	kg	1.50E-5	99.7	0.3	1	5.12	
	Carbon monoxide, biogenic	-	-	kg	1.94E-5	99.7	0.3	1	5.12	
	Chlorine	-	-	kg	4.61E-7	99.7	0.3	1	1.63	
	Chromium	-	-	kg	1.01E-8	99.7	0.3	1	5.12	
	Chromium VI	-	-	kg	1.02E-10	99.7	0.3	1	5.12	
	Copper	-	-	kg	5.63E-8	99.7	0.3	1	5.12	
	Dinitrogen monoxide	-	-	kg	5.63E-5	99.7	0.3	1	1.63	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	8.59E-14	99.7	0.3	1	3.10	
	Fluorine	-	-	kg	1.28E-7	99.7	0.3	1	1.63	
	Formaldehyde	-	-	kg	3.60E-7	99.7	0.3	1	1.63	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	2.52E-6	99.7	0.3	1	1.63	
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	8.59E-6	99.7	0.3	1	1.63	
	Lead	-	-	kg	6.37E-8	99.7	0.3	1	5.12	
	Magnesium	-	-	kg	9.24E-7	99.7	0.3	1	5.12	
	Manganese	-	-	kg	4.38E-7	99.7	0.3	1	5.12	
	Mercury	-	-	kg	7.68E-10	99.7	0.3	1	5.12	
	Methane, biogenic	-	-	kg	1.20E-6	99.7	0.3	1	1.63	
	m-Xylene	-	-	kg	3.33E-7	99.7	0.3	1	1.63	
	Nickel	-	-	kg	1.54E-8	99.7	0.3	1	5.12	
	Nitrogen oxides	-	-	kg	1.13E-4	99.7	0.3	1	1.63	
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.69E-6	99.7	0.3	1	1.63	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	3.05E-8	99.7	0.3	1	3.10	
	Particulates, < 2.5 um	-	-	kg	1.39E-5	99.7	0.3	1	3.10	
	Phenol, pentachloro-	-	-	kg	2.25E-11	99.7	0.3	1	1.63	
	Phosphorus	-	-	kg	7.68E-7	99.7	0.3	1	1.63	
	Potassium	-	-	kg	5.99E-5	99.7	0.3	1	5.12	
	Sodium	-	-	kg	3.33E-6	99.7	0.3	1	5.12	
	Sulfur dioxide	-	-	kg	6.37E-6	99.7	0.3	1	1.32	
	Toluene	-	-	kg	8.32E-7	99.7	0.3	1	1.63	
	Zinc	-	-	kg	7.68E-7	99.7	0.3	1	5.12	

16.8 Ethanol from rye, RER

16.8.1 System characterization

The system described in this paragraph includes the production of hydrated ethanol and DDGS from rye and the subsequent dehydration to ethanol 99.7% (wt.) in the European context (Fig. 16.10).

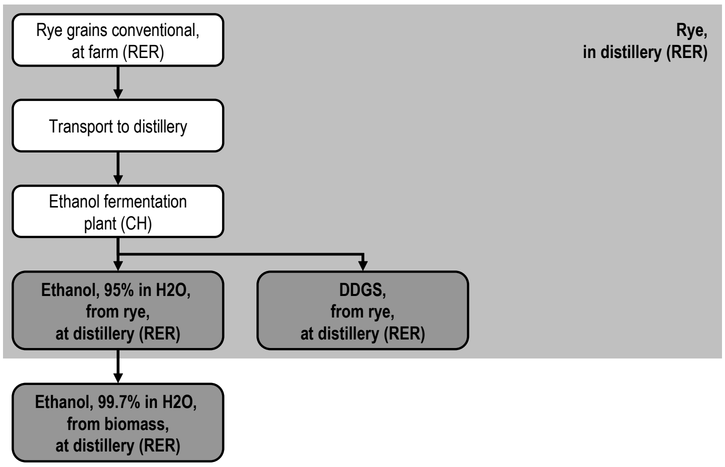


Fig. 16.10 Ethanol from rye, RER: system definition and boundaries.

The description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse (ENERS 2005; INTERIS 2002). The ethanol plant considered in this case processes 134 kt/yr of rye grains, and produces approx. 41 kt/yr of hydrated ethanol (95% wt.) as well as 47 kt/yr of DDGS (92% wt. dry matter).

The process considered here being almost identical to the conversion of potatoes, it is not described again here. The reader is advised to refer to the corresponding paragraph (paragraph 16.6). However, it is worth noting that variations exist in industrial processes (in terms of configuration or emerging technologies). Different processes may therefore imply changes in the energy consumption compared to what is described in this report. The differences, however, are not considered very significant.

According to the data from Tab. 16.20, 1 ton of rye grains (60% starch, 25% non-sugars, 15% water) results in:

- 293.7 kg of hydrated ethanol (95% wt., dry basis);
- 353.9 kg of DDGS (92% dry matter, 8% water).

Allocation between ethanol and DDGS is performed, based on quoted market prices (Krummenacher 2006, European Commission 2005; Punter et al. 2004) of anhydrous ethanol (i.e. 0.65 €/l) and cereals DDGS (i.e. 100 €/t) in the European Union. The resulting allocation factors are indicated in Tab. 16.19.

Tab. 16.19 Allocation factors in the production of ethanol from rye grains (RER).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Saccharification Fermentation Distillation	Hydrated ethanol	98.1%	51.7%	12.7%	55.9%
	DDGS	1.9%	48.3%	87.3%	44.1%
Stillage treatment	Hydrated ethanol	0.0%	0.0%	0.0%	0.0%
	DDGS	100.0%	100.0%	100.0%	100.0%

The dehydration of hydrated ethanol (95% wt.) from the distillation to anhydrous ethanol (99.7% wt.) is done by means of molecular sieves with regeneration by difference of pressure. The hydrated ethanol is overheated prior to dehydration, in order to avoid any risk of condensation in the adsorbers. The alternation of adsorption and desorption cycles makes the production of anhydrous ethanol continuous.

The ratio of hydrated to anhydrous ethanol (wet basis) is equal to 0.997/0.95, i.e. 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

16.8.2 LCI of 'Rye, in distillery, RER'

The production of ethanol and DDGS from rye is described in detail in paragraph 16.8.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.20 presents the yields of anhydrous ethanol (99.7% wt.) and DDGS from rye (more generally, from cereals), according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

The ethanol yield considered here is taken as the average value according to the quoted references (see Tab. 16.20).

Tab. 16.20 Literature review ethanol yields from rye (cereals).

Reference	Year	Yields	
		Rye (cereals) / RER	
		Ethanol 99.7% wt. [kg/t]	DDGS [kg/t]
ADEME 2002	2002	283.3	
Enguidanos et al. 2002	2002	278.2	
INTERIS 2002	2002	296.2	362.5
Bullard et al. 2003	2003	282.2	
Mehlin et al. 2003	2003	293.5	
O'Connor 2003	2003	274.2	380.0
PRA 2003	2003	294.1	
Woods & Bauen 2003	2003	296.2	310.0
LASEN 2004b	2004	298.1	362.4
Punter et al. 2004	2004	285.8	325.8
ENERS 2005	2005	297.1	362.4
VIEWLS 2005	2005	320.0	395.0
Krummenacher 2006	2006	331.2	333.3
Average		**294.6**	**353.9**
This study (ethanol 99.7% wt. wet basis)		**294.6**	**353.9**
This study (ethanol 95% wt. wet basis)		**309.2**	**353.9**
This study (ethanol 95% wt. dry basis)		**293.7**	**353.9**

Unless stated otherwise, the data below is from (ENERS 2005) and given per ton of rye grains.

Rye grains are transported to the distillery over an average distance of 70 km, of which 10 km are done by tractor and 60 km by train.

As far as energy is concerned, the electricity and heat consumed in the process amount to 122 kWh and 2'180 MJ per ton of grains, distributed over pretreatment and saccharification (23.8 kWh and 217 MJ), fermentation and distillation (17.4 kWh and 881 MJ) and stillage treatment (80.8 kWh and 1'082 MJ). Additional natural gas (2'073 MJ) is burned in the drying of DDGS (before granulation).

Raw materials used in the process include sulphuric acid (7.5 kg), soda powder (11.2 kg), and N-based nutrients in the form of ammonium sulphate (3.0 kg N) and diammonium phosphate (3.0 kg N). The transport distances for the delivery of raw materials include 50 km by 28t lorry and 600 km by train, based on the ecoinvent guidelines.

The consumption of water amounts to 1'250 kg per ton of rye grains. Liquid effluents (incl. flegmasses from the distillation stage and wastewater from stillage treatment) amount to 0.885 m^3.

The infrastructure of the ethanol distillery is described in the 'ethanol fermentation plant' dataset, with a production capacity of 90'000 t/yr (i.e. a feed capacity of 305 kt/yr of rye grains) over a lifetime of 20 years. The actual infrastructure input (excluding dehydration) is 1.48E-7 unit per ton of grains.

Direct carbon dioxide (CO_2) emissions from the fermentation process amount to 301 kg (i.e. 0.972 kg per kg of hydrated ethanol or 1.020 kg per kg of anhydrous ethanol). A correction of 429 kg (input and output) is applied to satisfy the carbon balance (according to the carbon content) between ethanol and DDGS in spite of the economic allocation. Finally, waste heat to air amounts to 1'870 MJ.

The two outputs of the MO-process 'rye, in distillery' include:

- ethanol, 95% in H2O, from rye, at distillery (dry basis): **293.7 kg/t rye**;
- DDGS, from rye, at distillery: **353.9 kg/t rye**.

The economic allocation approach (paragraph 16.7.2, Tab. 16.19) is applied, with factors for common stages (including the feedstock) of 98.1% and 1.9% respectively. The unit process raw data is shown in Tab. 16.21.

16.8.3 LCI of 'Ethanol, 99.7% in H2O, from biomass, at distillation, RER'

The production of anhydrous ethanol 99.7% from hydrated ethanol 95% (dehydration) is described in detail in paragraph 16.8.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study. The unit process raw data is indicated in Tab. 16.21.

The ratio of hydrated to anhydrous ethanol (wet basis) is equal to 0.997/0.95, i.e. 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

The energy use for the dehydration of anhydrous ethanol is taken from (ENERS 2005). The electricity and steam required amount to 9.1 kWh and 1'015 MJ, respectively, per ton of anhydrous ethanol.

Liquid effluents, corresponding to the water and so-called bad taste alcohol (or fusel oil) removed from the ethanol, amount to 49.6 l per ton of anhydrous ethanol and are eliminated in a wastewater treatment plant.

The infrastructure input (dehydration only) is 5.30E-8 unit per ton of anhydrous ethanol. Finally, waste heat to air (corresponding to the electricity consumption expressed in MJ) amount to 33 MJ.

Tab. 16.21 Unit process raw data of the dataset 'rye, in distillery', RER.

	Name	Location	InfrastructureProcess	Unit	rye, in distillery	ethanol, 95% in H2O, from rye, at distillery	DDGS, from rye, at distillery	ethanol, 99.7% in H2O, from biomass, at distillation	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	ethanol, 95% in H2O, from rye, at distillery	RER	0	kg	2.94E-01	100.0					
product	DDGS, from rye, at distillery	RER	0	kg	3.54E-01		100.0				
product	ethanol, 99.7% in H2O, from biomass, at distillation	RER	0	kg				1.00E+00			
resource, in air	Carbon dioxide, in air	-	-	kg	4.29E-1	0.0	100.0		1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	rye grains conventional, at farm	RER	0	kg	1.00E+0	98.1	1.9		1	1.21	(1,2,1,1,1,5); etha+ project Alcosuisse, industrial data
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.07E+0	0.0	100.0		1	1.21	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	2.18E+0	49.4	50.6	1.02E+0	1	1.21	
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.22E-1	33.2	66.8	9.15E-3	1	1.21	
	tap water, at user	RER	0	kg	1.25E+0	98.1	1.9		1	1.21	
	sulphuric acid, liquid, at plant	RER	0	kg	7.47E-3	98.1	1.9		1	1.21	
	soda, powder, at plant	RER	0	kg	1.12E-2	98.1	1.9		1	1.21	
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	2.99E-3	98.1	1.9		1	1.21	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	2.99E-3	98.1	1.9		1	1.21	
	transport, tractor and trailer	CH	0	tkm	1.00E-2	98.1	1.9		1	2.05	
	ethanol fermentation plant	CH	1	unit	1.48E-10	49.7	50.3	5.30E-11	1	3.05	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	8.85E-4	41.3	58.7	4.96E-5	1	1.21	
	ethanol, 95% in H2O, from rye, at distillery	RER	0	kg				1.00E+0	1	1.05	(1,1,1,1,1,1); Product, calculation
	transport, freight, rail	RER	0	tkm	7.48E-2	98.1	1.9		1	2.09	(4,5,na,na,na,na); Assumption, standard distances
	transport, lorry 32t	RER	0	tkm	2.46E-3	98.1	1.9		1	2.09	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	7.30E-1	100.0	0.0		1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.90E+0	33.2	66.8	3.29E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

16.9 Ethanol from sugarcane molasses, BR

16.9.1 System characterization

The system described in this paragraph includes the production of sugar, hydrated ethanol (95% vol.), bagasse, electricity and vinasse (stillage) from sugarcane in an integrated sugar refinery, in the Brazilian context (Fig. 16.11). The dehydration to ethanol 99.7% wt. is described in chapter 14.9.

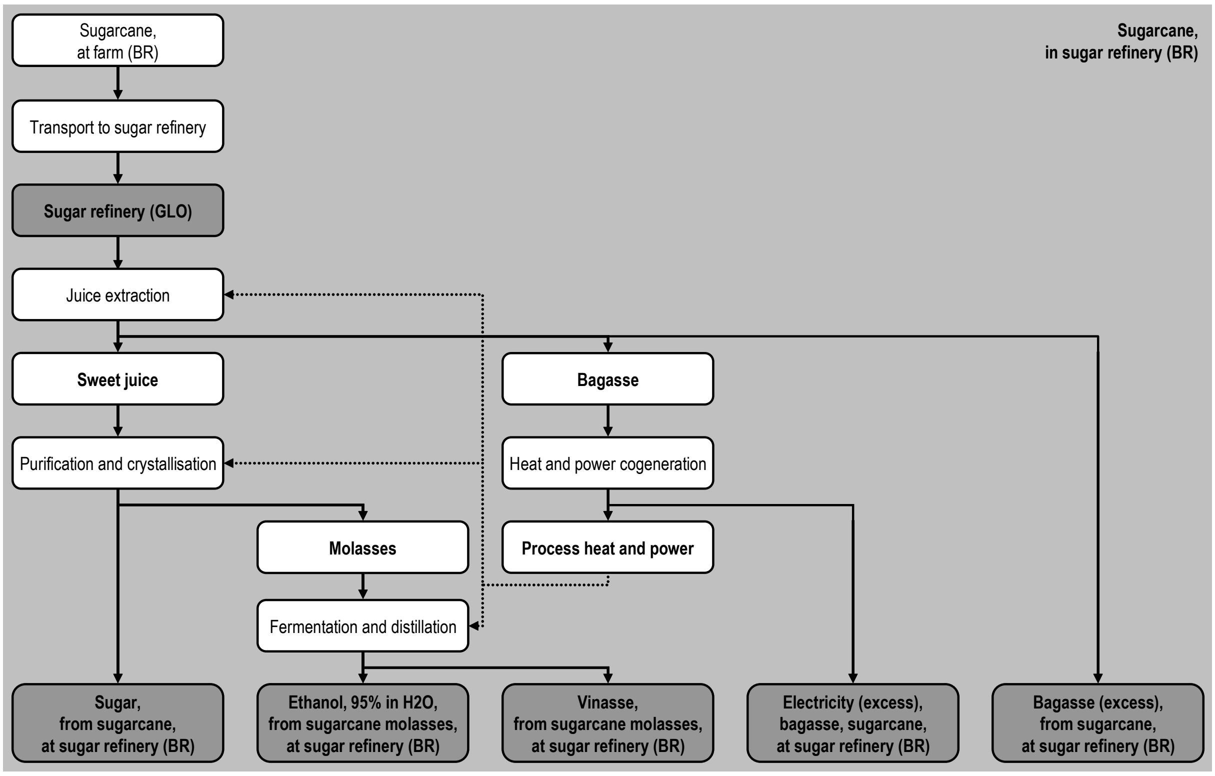


Fig. 16.11 Ethanol from sugarcane molasses, BR: system definition and boundaries.

The description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse (ENERS 2005; INTERIS 2002) and additional related references including (Steiner & Tuchschmid 2006; Woods 2000; LASEN 2004a).

On the basis of case study in (Woods 2000), the feed capacity considered for the sugar refinery is taken as 2'400 kt/yr of sugarcane. According to (Borrorea et al. 2003), this corresponds to a medium-to-large scale refinery in the Brazilian context. The corresponding sugar and hydrated ethanol outputs are 294 kt and 23 kt per year respectively. The refinery operates approx. 270 days/yr (Macedo 2004).

As the cane arrives at the mill (essentially by truck), it is weighed and sampled to measure the fibre and sucrose content, and washed in order to remove impurities such as earth, sand, etc. (Copersucar 2006). The subsequent stage, i.e. juice extraction, is a critical stage in the processing chain from the point of view of bioenergy, as it leads to three more potential processing routes for the sugars : (1) production of sugar and ethanol (here, molasses, and possibly part of the sweet juice, are used as feedstock for the production of ethanol), (2) production of sugar and animal feed (molasses are used as animal feed) and (3) production of ethanol only (Woods 2000).

In this chapter, only the first option (1) is considered. Therefore, sugarcane molasses are not considered as an actual output of the sugar mill, but rather as an intermediate product, used as a feedstock for fuel-ethanol production in an integrated sugar mill, coupled with a distillery (Fig. 16.11). This corresponds to the actual situation in Brazil (Steiner & Tuchschmid 2006).

There are two methods for the separation of the sugars from the bagasse (fibres). The older technology employs a roller mill tandem which effectively squeezes the sugar-rich juice from the fibre. The second method, called 'diffusion', extracts the sugars by washing them out of the fibres (see paragraph 16.5). Although diffusion can usually achieve higher rates of sugar extraction than milling, the most frequent technique in Brazil is milling.

Two primary streams exit the mill, namely (1) the sugar rich juice (or sweet juice), and (2) the fibre-rich bagasse (Fig. 16.12).

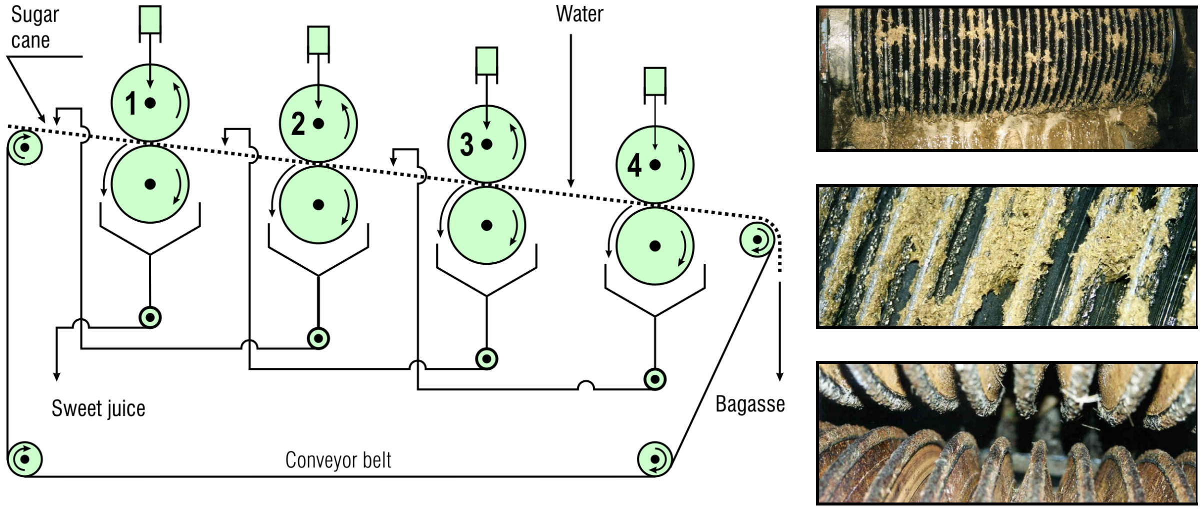


Fig. 16.12 Schematic representation of the juice extraction process (milling technique). Adapted from (Cundiff 1993).

In sugarcane stems, the fibrous (structural) matter (i.e. the bagasse), and sugars are present in approximately equal amounts (in this case, 14.5% wt. sugars and 13% wt. fibres). As a result of going through the juice separation process, virtually all the sugars are removed from the fibres. Given the initial water contained in the stem and the addition of water during the milling process, the bagasse exits the mill at about 50% moisture and has an energy density of 9 MJ/kg (compared to 18.8 MJ/kg if oven dry). The bagasse is therefore often pressed to remove more water, up to 75-80% wt. dry matter.

Most of the bagasse is burnt to produce steam (to provide rotary power for the mills and process heat) and electricity. Excess electricity is sold to the national grid. According to (Macedo 2004; Woods 2000; Goldemberg 2000), surplus bagasse amounts to approx. 10% of the initial bagasse resulting from the extraction process. It is usually stored and sold on the market for various purposes, depending on the location of the sugar mill.

The energy used in sugar and ethanol production from sugarcane is therefore completely produced by burning the bagasse (Macedo 2004; Steiner & Tuchschmid 2006; Copersucar 2006). Sugar mills are hence self-sufficient and do not use external energy.

The sweet juice resulting from the extraction process is processed to sugar and molasses, with the latter being then converted to ethanol (Fig. 16.11). Apart from the extraction stage, the production of sugar and molasses from sugarcane is very similar to the process described in paragraph 16.5 for sugar beets. Likewise, the production of ethanol from sugarcane molasses is analogous to the conversion of sugar beet molasses to ethanol described in the same paragraph.

According to the composition of sugarcane and the data from Tab. 16.23 and (Steiner & Tuchschmid 2006; Woods 2000; LASEN 2004a; ZAF 2002; ZAF 2005; UNICA 2004; Rossell 2005; Cheesman 2004), 1 ton of sugarcane (14.5% sugars, 13% fibres, 1% non-sugars and 71.5% water) results in:

- 122.3 kg of pure white sugar (100% dry matter);
- 9.0 kg of hydrated ethanol (95% wt., dry basis);
- 30.3 kWh of electricity (net production);
- 19.1 kg of excess bagasse (78.7% dry matter, 21.2% water);
- 93.8 kg of vinasse (15% dry matter, 85% water).

Allocation between the various outputs is performed, based on quoted BR market prices (Steiner & Tuchschmid 2006) of anhydrous ethanol (0.82 R$/l), sugar (612 R$/t), bagasse (40 R$/t) and electricity (57.5 R$/MWh). The vinasse is returned to the sugarcane farmers as a fertilizer substitute and has no actual economic value (0 R$/t). The resulting allocation factors are indicated for each group of process stages in Tab. 16.22.

Tab. 16.22 Allocation factors in the combined production of sugar and ethanol from sugarcane (BR).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Washing Slicing Diffusion	Sugar	86.4%	77.6%	74.6%	85.1%
	Hydrated ethanol	10.8%	4.4%	2.1%	8.0%
	Excess bagasse	0.8%	6.4%	2.8%	6.7%
	Excess electricity	2.0%	7.0%	0.0%	0.0%
	Vinasse	0.0%	4.7%	20.5%	0.2%
Purification Crystallisation	Sugar	88.9%	89.6%	76.7%	91.2%
	Hydrated ethanol	11.1%	5.0%	2.1%	6.9%
	Excess bagasse	0.0%	0.0%	0.0%	0.0%
	Excess electricity	0.0%	0.0%	0.0%	0.0%
	Vinasse	0.0%	5.4%	21.1%	1.9%
Ethanol production	Sugar	0.0%	0.0%	0.0%	0.0%
	Hydrated ethanol	100.0%	48.3%	9.2%	78.4%
	Excess bagasse	0.0%	0.0%	0.0%	0.0%
	Excess electricity	0.0%	0.0%	0.0%	0.0%
	Vinasse	0.0%	51.7%	90.8%	21.6%

16.9.2 LCI of ‘Sugarcane, in sugar refinery, BR’

The production of sugar and ethanol from sugarcane in Brazil (BR) is detailed in paragraph 16.9.1. The present paragraph describes the actual life cycle inventory of the process as defined in this study.

The data in Tab. 16.23 below shows the yields of sugar, molasses (as an intermediate product) and ethanol from sugarcane, according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively). In the present case, the yields considered are adapted to match the composition of sugarcane as described in chapter 10. The values used in this study are actually very close to the average according to the references consulted.

Tab. 16.23 Literature review sugar and ethanol yields from sugarcane.

Reference	Year	Yields		
			Sugarcane / BR	
		Sugar [kg/t]	Molasses [kg/t]	Ethanol 99.7% wt. [kg/t]
Schleser 1994	1994	104.5	30.0	9.2
Woods 2000	2000	122.2	37.0	5.9
Möllersten et al. 2003	2003	121.0	42.0	11.5
UNICA 2004	2004	118.0		10.0
Rabotovao 2005	2005	120.0		9.5
Rossell 2005	2005	120.0		8.8
Steiner & Tuchschmid 2006	2006	122.3		11.6
Average		**118.3**	**36.3**	**9.5**
This study (ethanol 99.7% wt. wet basis)		**122.3**	**36.8**	**9.1**
This study (ethanol 95% wt. wet basis)		**122.3**	**36.8**	**9.5**
This study (ethanol 95% wt. dry basis)		**122.3**	**36.8**	**9.0**

Unless stated otherwise, the data below is given per ton of sugarcane. Various references are compiled to establish the LCI of sugar and ethanol production from sugarcane, including (Macedo 2004; Steiner & Tuchschmid 2006; ZAF 2002; ENERS 2005; INTERIS 2002; Woods 2000).

Sugarcane is transported to the distillery from nearby fields over an average distance of 20 km, of which 2 km are done by 16t lorry and 18 km by 32t lorry (Macedo 2004). Here, datasets for transport in the European context are used.

As far as energy is concerned, the respective consumptions of electricity and heat amount to 29.0 kWh and 1'594 MJ per ton of sugarcane, distributed over the stages of washing and extraction (3.6 kWh and 1'023 MJ), pressing of the bagasse (0.9 kWh and 256 MJ), purification and crystallisation (24.0 kWh and 251 MJ), and ethanol production (0.4 kWh and 48 MJ). All the heat and power are produced locally by burning the pressed bagasse. Some excess electricity is also produced as a by-product of sugar and ethanol, which amounts to 30.3 kWh per ton of sugarcane. As indicated in paragraph 16.8.3, 90% of the bagasse are enough to supply energy to the complete process. The remaining 10% (19.1 kg per ton of sugarcane) are sold on the market, as by-products of sugar, ethanol and excess electricity.

Raw materials used in the process include sulphuric acid (11.9 kg), soda powder (0.27 kg), organic and inorganic chemicals (0.07 kg and 0.10 kg respectively), N-based nutrients for bacterial growth in the form of ammonium sulphate and diammonium phosphate (0.08 kg N and 0.12 kg N respectively), hard coal coke (1.96 kg), limestone (23.7 kg), and lubricating oil (0.01 kg). The railway network being very poorly developed in Brazil, the delivery of raw materials is considered to be performed by road only (32t lorry), over an average distance of 650 km. Limestone being more available around sugar mills, a distance of only 100 km is considered.

The consumption of water amounts to 1'073 kg per ton of sugarcane. Most of the liquid effluents in the Brazilian sugar and ethanol industry are returned to the fields as fertilizer complements or disposed of with no specific treatment in the proximate environment of the plant. In this case, the vinasse resulting from the distillation process is taken into account as by-product of sugar and ethanol, with a zero economic value.

The infrastructure of the sugar refinery is described in the 'sugar refinery' dataset (paragraph 16.5.2), with a sugar production capacity of 200'000 t/yr (i.e. a feed capacity of 1'635 kt/yr of sugarcane) over a lifetime of 50 years, i.e. 1.22E-8 unit per ton of sugarcane. The infrastructure of the ethanol distillery is described in the 'ethanol fermentation plant' dataset, with a production capacity of 90'000 t/yr (i.e. a feed capacity of 9'890 kt/yr of sugarcane) over a lifetime of 20 years. The actual infrastructure input (excluding the dehydration stage) is 3.79E-9 unit per ton of sugarcane.

Direct emissions of the complete process include carbon dioxide (CO_2) emissions from the fermentation process (9.2 kg, i.e. 0.972 kg per kg of hydrated ethanol or 1.020 kg per kg of anhydrous ethanol), and emissions from the combustion of the bagasse. Here again, the process 'wood chips, burned in cogen 6400kWth' is adapted and used to model the combustion. The properties and characteristics of pressed bagasse are given in Tab. 16.24 and compared with wood chips (u=40%).

Tab. 16.24 Characteristics and properties of pressed sugarcane bagasse, compared with wood chips (u=40%).

	Sugarcane bagasse		Wood chips, u=40%	
Water content	21.3	% w/w	28.6	% w/w
Dry matter content	78.7	% w/w	71.4	% w/w
Carbon content (dry matter basis)	44.3	% w/w	49.4	% w/w
Higher heating value	19.6	MJ/kg	20.2	MJ/kg
Lower heating value	15.4	MJ/kg	14.4	MJ/kg
Dry matter input	0.787	kg/kg	0.714	kg/kg
Carbon input	0.349	kg/kg	0.353	kg/kg
Energy input	15.433	MJ/kg	14.400	MJ/kg
Heat production	10.365	MJ/kg	11.045	MJ/kg
Electricity production	0.386	kWh/kg	0.331	kWh/kg

The process 'wood chips, burned in cogen 6400kWth' is adapted according to the same rules as in paragraph 16.7.2.

The two outputs of the MO-process 'sugarcane, in sugar refinery' include:

- sugar, from sugarcane, at sugar refinery: **122.3 kg/t sugarcane**;
- ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery: **9.0 kg/t sugarcane**;
- electricity, bagasse, sugarcane, at sugar refinery: **30.3 kWh/t sugarcane**;
- bagasse, from sugarcane, at sugar refinery: **19.1 kg/t sugarcane**;
- vinasse, from sugarcane molasses, at sugar refinery: **93.8 kg/t sugarcane**.

The economic allocation approach (paragraph 16.8.3, Tab. 16.22) is used, with factors of 84.3%, 13.6%, 0.6%, 1.5% and 0.0% respectively (applicable to common stages including the feedstock). The unit process raw data is indicated in Tab. 16.25.

Tab. 16.25 Unit process raw data of the dataset 'sugarcane, in sugar refinery', BR.

	Name	Location	InfrastructureProcess	Unit	sugarcane, in sugar refinery	sugar, from sugarcane, at sugar refinery	ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery	bagasse, from sugarcane, at sugar refinery	electricity, bagasse, sugarcane, at sugar refinery	vinasse, from sugarcane molasses, at sugar refinery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				BR	BR	BR	BR	BR	BR			
	InfrastructureProcess				0	0	0	0	0	0			
	Unit				kg	kg	kg	kg	kWh	kg			
product	sugar, from sugarcane, at sugar refinery	BR	0	kg	1.22E-01	0.0	0.0	81.3	0.0	18.7			
product	ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery	BR	0	kg	9.03E-03	86.4	10.8	0.8	2.0	0.0			
product	bagasse, from sugarcane, at sugar refinery	BR	0	kg	1.91E-02	86.4	10.8	0.8	2.0	0.0			
product	electricity, bagasse, sugarcane, at sugar refinery	BR	0	kWh	3.03E-02	79.7	17.8	0.7	1.8	0.0			
product	vinasse, from sugarcane molasses, at sugar refinery	BR	0	kg	9.38E-02	7.9	92.1	0.0	0.0	0.0			
resource, in air	Carbon dioxide, in air	-	-	kg	2.55E-2	0.0	100.0	0.0	0.0	0.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	sugar cane, at farm	BR	0	kg	1.00E+0	0.0	100.0	0.0	0.0	0.0	1	1.09	(2,1,1,1,1,3); Average sugar and ethanol yields in Brazil, literature survey
	sulphur dioxide, liquid, at plant	RER	0	kg	3.75E-4	88.9	11.1	0.0	0.0	0.0	1	1.24	(3,3,1,3,1,5); Data from sugar and ethanol producers in Brazil
	tap water, at user	RER	0	kg	1.07E+0	7.9	92.1	0.0	0.0	0.0	1	1.25	(4,3,1,5,1,3); Average consumption of water in a sugar refinery in Brazil, literature
	sulphuric acid, liquid, at plant	RER	0	kg	5.55E-4	88.4	11.3	0.1	0.2	0.0	1	1.33	(2,4,1,3,3,5); etha+ project Alcosuisse, industrial data
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	7.96E-5	88.9	11.1	0.0	0.0	0.0	1	1.33	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	1.19E-4	0.0	100.0	0.0	0.0	0.0	1	1.33	
	soda, powder, at plant	RER	0	kg	2.69E-4	85.9	11.5	0.8	1.9	0.0	1	1.33	
	chemicals organic, at plant	GLO	0	kg	8.25E-5	88.9	11.1	0.0	0.0	0.0	1	1.33	
	chemicals inorganic, at plant	GLO	0	kg	1.04E-4	86.4	10.8	0.8	2.0	0.0	1	1.24	(2,4,1,2,1,5); Data from sugar producer in Switzerland
	lubricating oil, at plant	RER	0	kg	1.92E-5	86.4	10.8	0.8	2.0	0.0	1	1.27	(2,4,1,5,1,5); Average consumption of limestone in a sugar refinery, global value
	limestone, milled, loose, at plant	CH	0	kg	2.37E-2	86.4	10.8	0.8	2.0	0.0	1	1.27	(2,4,1,5,1,5); Industrial data from Brazil, for sugarcane milling
	hard coal coke, at plant	RER	0	MJ	1.96E-3	88.4	11.0	0.2	0.4	0.0	1	1.24	(2,4,1,2,1,5); Data from sugar producer in Switzerland
	transport, lorry 32t	RER	0	tkm	2.51E-2	88.9	11.1	0.0	0.0	0.0	1	2.06	(2,4,1,3,1,5); Industrial data from Brazil, for sugarcane delivery to sugar refinery; includes delivery of raw materials according to ecoinvent guidelines, adapted to Brazilian conditions
	transport, lorry 16t	CH	0	tkm	2.00E-3						1	2.06	(2,4,1,3,1,5); Industrial data from Brazil, for sugarcane delivery to sugar refinery
	sugar refinery	GLO	1	unit	1.22E-11	84.3	13.6	0.6	1.5	0.0	1	3.06	(2,4,1,2,1,5); Sugar-specific infrastructure, given sugar refinery characteristics
	ethanol fermentation plant	CH	1	unit	3.79E-12	84.3	13.6	0.6	1.5	0.0	1	3.07	(2,4,1,5,1,5); Ethanol specific infrastructure, given ethanol plant characteristics
	ammonia, liquid, at regional storehouse	RER	0	kg	1.45E-8	84.3	13.6	0.6	1.5	0.0	1	1.35	(4,4,2,5,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (pressed sorghum bagasse)
	chlorine, liquid, production mix, at plant	RER	0	kg	5.79E-7	84.3	13.6	0.6	1.5	0.0	1	1.35	
	sodium chloride, powder, at plant	RER	0	kg	7.24E-6	84.3	13.6	0.6	1.5	0.0	1	1.35	
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	5.79E-6	84.3	13.6	0.6	1.5	0.0	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to landfarming	CH	0	kg	2.33E-4	84.3	13.6	0.6	1.5	0.0	1	1.35	
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	5.79E-6	84.3	13.6	0.6	1.5	0.0	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.33E-4	84.3	13.6	0.6	1.5	0.0	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	4.68E-4	84.3	13.6	0.6	1.5	0.0	1	1.35	
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	1.39E-6	83.8	12.6	0.0	3.7	0.0	1	1.35	
	water, decarbonised, at plant	RER	0	kg	1.39E-3	88.9	11.1	0.0	0.0	0.0	1	1.35	
	cogen unit 6400kWth, wood burning, building	CH	1	unit	4.26E-10	84.3	13.6	0.6	1.5	0.0	1	3.12	
	cogen unit 6400kWth, wood burning, common components for	CH	1	unit	1.70E-9	84.3	13.6	0.6	1.5	0.0	1	3.12	
	cogen unit 6400kWth, wood burning, components for electricity only	CH	1	unit	1.70E-9	84.3	13.6	0.6	1.5	0.0	1	3.12	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.42E-1	84.3	13.6	0.6	1.5	0.0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Carbon dioxide, fossil	-	-	kg	1.04E-4	84.3	13.6	0.6	1.5	0.0	1	1.05	(1,1,1,1,1,1); Calculation, according to consumption of
	Heat, waste	-	-	MJ	2.18E+0	84.3	13.6	0.6	1.5	0.0	1	1.31	(2,3,1,1,3,5); ecoinvent guidelines, calculation from electricity consumption and
	Acetaldehyde	-	-	kg	1.08E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	(4,4,2,5,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (pressed sorghum bagasse)
	Ammonia	-	-	kg	3.07E-6	84.3	13.6	0.6	1.5	0.0	1	1.41	
	Arsenic	-	-	kg	1.77E-9	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Benzene	-	-	kg	1.44E-6	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Benzene, ethyl-	-	-	kg	4.75E-8	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Benzene, hexachloro-	-	-	kg	1.14E-14	84.3	13.6	0.6	1.5	0.0	1	3.12	
	Benzo(a)pyrene	-	-	kg	7.92E-10	84.3	13.6	0.6	1.5	0.0	1	3.12	
	Bromine	-	-	kg	1.06E-7	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Cadmium	-	-	kg	1.24E-9	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Calcium	-	-	kg	1.03E-5	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Carbon monoxide, biogenic	-	-	kg	1.11E-5	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Chlorine	-	-	kg	3.18E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Chromium	-	-	kg	7.00E-9	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Chromium VI	-	-	kg	7.07E-11	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Copper	-	-	kg	3.89E-8	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Dinitrogen monoxide	-	-	kg	4.06E-6	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	4.91E-14	84.3	13.6	0.6	1.5	0.0	1	3.12	
	Fluorine	-	-	kg	8.83E-8	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Formaldehyde	-	-	kg	2.06E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	1.44E-6	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	4.91E-6	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Lead	-	-	kg	4.40E-8	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Magnesium	-	-	kg	6.38E-7	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Manganese	-	-	kg	3.02E-7	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Mercury	-	-	kg	5.30E-10	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Methane, biogenic	-	-	kg	6.88E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	m-Xylene	-	-	kg	1.90E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Nickel	-	-	kg	1.06E-8	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Nitrogen oxides	-	-	kg	1.55E-4	84.3	13.6	0.6	1.5	0.0	1	1.65	
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.66E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	1.74E-8	84.3	13.6	0.6	1.5	0.0	1	3.12	
	Particulates, < 2.5 um	-	-	kg	7.11E-5	84.3	13.6	0.6	1.5	0.0	1	3.12	
	Phenol, pentachloro-	-	-	kg	1.28E-11	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Phosphorus	-	-	kg	5.30E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Potassium	-	-	kg	4.13E-5	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Sodium	-	-	kg	2.30E-6	84.3	13.6	0.6	1.5	0.0	1	5.13	
	Sulfur dioxide	-	-	kg	4.40E-6	84.3	13.6	0.6	1.5	0.0	1	1.35	
	Toluene	-	-	kg	4.75E-7	84.3	13.6	0.6	1.5	0.0	1	1.65	
	Zinc	-	-	kg	5.30E-7	84.3	13.6	0.6	1.5	0.0	1	5.13	

16.10 Ethanol from corn, US

16.10.1 System characterization

The system described in this paragraph includes the production of hydrated ethanol and DDGS from corn grains and the subsequent dehydration to ethanol 99.7% (wt.) in the US context (Fig. 16.13).

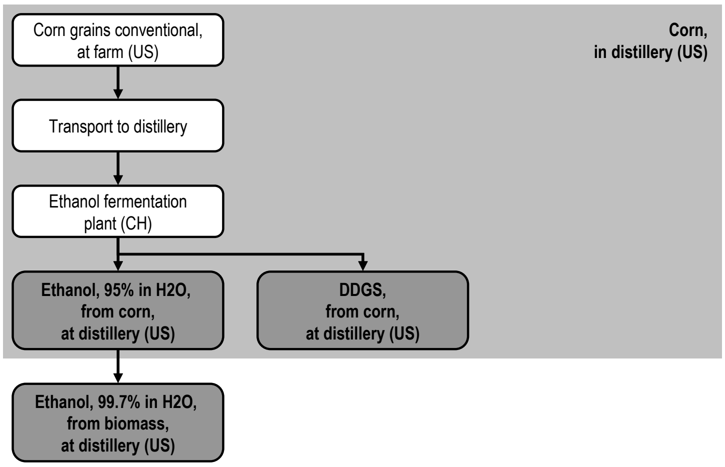


Fig. 16.13 Ethanol from corn, US: system definition and boundaries.

Although there are many US studies describing the production of ethanol from corn (see exact references in Tab. 16.27), the description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse (ENERS 2005; INTERIS 2002). The data used in this inventory, however, agrees with the references cited in Tab. 16.27 on most aspects. This choice is mainly dictated by the wish to keep as much coherence as possible between the various production chains, and the wish to use data as detailed and disaggregated as possible (e.g. distinction between the energy used in pre-distillation stages and stillage tratment stages, energy integration between the various stages, all making the allocation procedure much more accurate).

The process described corresponds to the dry-milling corn-to-ethanol technology. Ethanol production facilities in the US include both wet-milling and dry-milling operations. Dry mills are usually smaller and are built primarily to manufacture ethanol. Wet mills are “corn refineries” producing high-value co-products such as high-fructose corn syrup, dextrose, or yet glucose syrup. Dry milling today accounts for about 45 percent of total US ethanol production and is expected to represent 80% of ethanol production by 2012 (Graboski 2002).

The ethanol distillery considered here processes 134 kt/yr of corn grains, and produces approximately 43 kt/yr of hydrated ethanol (95% wt.) as well as 43 kt/yr of DDGS (92% wt. dry matter). The process being almost identical to the conversion of potatoes to bioethanol (paragraph 16.6), it is not described again here.

According to the data from Tab. 16.27, 1 ton of (dried) corn grains (60% starch, 26% non-sugars, 14% water) results in:

- 306.4 kg of hydrated ethanol (95% wt., dry basis);
- 320.7 kg of DDGS (92% dry matter, 8% water).

Allocation between ethanol and DDGS is performed, based on quoted US market price (Dale & Tyner 2005; Tiffany & Eidman 2003; Shapouri et al. 2002; PRA 2005; FAPRI 2005) of anhydrous ethanol (i.e. 0.40 US$/l) and corn DDGS (i.e. 80 US$/t). The resulting allocation factors are indicated for each group of process stages in Tab. 16.26.

Tab. 16.26 Allocation factors in the production of ethanol from corn grains (US).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Saccharification Fermentation Distillation	Anhydrous ethanol	98.8%	51.7%	12.7%	55.2%
	DDGS	1.2%	48.3%	87.3%	44.8%
Stillage treatment	Anhydrous ethanol	0.0%	0.0%	0.0%	0.0%
	DDGS	100.0%	100.0%	100.0%	100.0%

Like in the case of ethanol from rye grains, the dehydration process of hydrated ethanol (95% wt.) to anhydrous ethanol (99.7% wt.) is performed by means of molecular sieves (see paragraph 16.7.2).

The ratio of hydrated to anhydrous ethanol (wet basis) is equal to 0.997/0.95, i.e. 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

16.10.2 LCI of 'Corn, in distillery, US'

The production of ethanol and DDGS from corn grains is described in detail in paragraph 16.10.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.27 shows the yields of anhydrous ethanol (99.7% wt.) and DDGS from corn grains, according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

The ethanol yield considered here corresponds to the average value according to the quoted references.

Tab. 16.27 Literature review ethanol yields from corn.

Reference	Year	Yields	
		Corn / US	
		Ethanol 99.7% wt. [kg/t]	DDGS [kg/t]
Marland & Turhollow 1990	1990	296.1	
Pimentel 1991	1991	296.1	
Keeney & DeLuca 1992	1992	303.3	
Morris & Ahmed 1992	1992	302.1	
Lorenz & Morris 1995	1995	302.1	
Shapouri et al. 1995	1995	299.7	312.1
Pimentel 1998	1998	296.1	
Levelton Engineering 1999	1999	318.7	
Wang et al. 1999	1999	302.1	
Beauvais et al. 2000	2000	261.5	364.5
McAloon et al. 2000	2000	305.7	298.2
Graboski 2002	2002	321.6	329.4
Kim & Dale 2002	2002	307.0	282.4
Pimentel 2002	2002	296.1	
Shapouri et al. 2002	2002	315.1	
Adrien et al. 2003	2003	336.6	327.8
Ferguson 2003	2003	315.1	
Pimentel 2003	2003	296.1	
PRA 2003	2003	316.3	280.9
Tiffany & Eidman 2003	2003	325.8	336.6
Coltrain 2004	2004	319.8	
Durante & Miltenberger 2004	2004	325.8	
IEA 2004	2004	300.4	
LASEN 2004a	2004	315.4	300.2
Shapouri et al. 2004	2004	314.9	
FAPRI 2005	2005	312.3	375.1
Pimentel & Patzek 2005	2005	295.5	
Average		**307.3**	**320.7**
This study (ethanol 99.7% wt. wet basis)		**307.3**	**320.7**
This study (ethanol 95% wt. wet basis)		**322.5**	**320.7**
This study (ethanol 95% wt. dry basis)		**306.4**	**320.7**

Unless stated otherwise, the data below is from (ENERS 2005) and given per ton of corn grains.

Corn grains are transported to the distillery over an average distance of 70 km, of which 10 km are done by tractor and 60 km by 16t lorry. Here, datasets for transport in the European context are used.

As far as energy is concerned, the electricity and heat consumed in the process amount to 123 kWh and 2’241 MJ per ton of grains, distributed over pretreatment and saccharification (24.0 kWh and 216 MJ), fermentation and distillation (17.6 kWh and 909 MJ) and stillage treatment (81.4 kWh and 1’116 MJ). Additional natural gas (2’171 MJ) is burned in the drying of DDGS (before granulation).

Raw materials used in the process include sulphuric acid (7.5 kg), soda powder (11.2 kg), and N-based nutrients in the form of ammonium sulphate (3.0 kg N) and diammonium phosphate (3.0 kg N). The transport distances for the delivery of raw materials include 100 km by 32t lorry and 600 km by train, based on the ecoinvent guidelines.

The consumption of water amounts to 1’310 kg per ton of corn grains. Liquid effluents (incl. flegmasses from the distillation stage and wastewater from stillage treatment) amount to 0.915 m^3.

The infrastructure of the ethanol distillery is described in the ‘ethanol fermentation plant’ dataset, with a production capacity of 90’000 t/yr (i.e. a feed capacity of 293 kt/yr of corn grains) over a lifetime of 20 years. The actual infrastructure input (excluding dehydration) is 1.54E-7 unit per ton of grains.

Direct carbon dioxide (CO_2) emissions from the fermentation process amount to 312 kg (i.e. 0.967 kg per kg of hydrated ethanol or 1.015 kg per kg of anhydrous ethanol). A correction of 462 kg (input and output) is applied to satisfy the carbon balance (according to the carbon content) between ethanol and DDGS in spite of the economic allocation. Finally, waste heat to air amounts to 3'070 MJ.

The two outputs of the MO-process 'corn, in distillery' include:

- ethanol, 95% in H2O, from corn, at distillery (dry basis): **306.4 kg/t corn**;
- DDGS, from corn, at distillery: **320.7 kg/t corn**.

The economic allocation (paragraph 16.9.2, Tab. 16.26) is used, with factors for common stages (including the feedstock) of 97.7% and 2.3% respectively. The unit process raw data is shown in Tab. 16.28.

16.10.3 LCI of 'Ethanol, 99.7% in H2O, from biomass, at distillation, US'

The production of anhydrous ethanol 99.7% from hydrated ethanol 95% (dehydration) is described in detail in paragraph 16.10.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study. The unit process raw data is indicated in Tab. 16.28.

The ratio of hydrated to anhydrous ethanol (wet basis) is equal to 0.997/0.95, i.e. 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

The energy use for the dehydration of anhydrous ethanol is taken from (ENERS 2005). The electricity and steam required amount to 8.8 kWh and 1002 MJ, respectively, per ton of anhydrous ethanol.

Liquid effluents, corresponding to the water and so-called fusel oil removed from ethanol, amount to 49.6 l per ton of anhydrous ethanol and are eliminated in a wastewater treatment plant.

The infrastructure input (dehydration only) is 5.30E-8 unit per ton of anhydrous ethanol. Finally, waste heat to air (corresponding to the electricity consumption expressed in MJ) amount to 32 MJ.

Tab. 16.28 Unit process raw data of the dataset 'corn, in distillery', US.

	Name	Location	InfrastructureProcess	Unit	corn, in distillery	ethanol, 95% in H2O, from corn, at distillery	DDGS, from corn, at distillery	ethanol, 99.7% in H2O, from biomass, at distillation	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				US	US	US	US			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	ethanol, 95% in H2O, from corn, at distillery	US	0	kg	3.06E-01	100.0					
product	DDGS, from corn, at distillery	US	0	kg	3.21E-01		100.0				
product	ethanol, 99.7% in H2O, from biomass, at distillation	US	0	kg				1.00E+00			
resource, in air	Carbon dioxide, in air	-	-	kg	4.62E-1	0.0	100.0		1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	corn, at farm	US	0	kg	1.00E+0	98.8	1.2		1	1.21	(1,2,1,1,1,5); etha+ project Alcosuisse, industrial data, cross checking with literature survey for US conditions
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	2.17E+0	0.0	100.0		1	1.21	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	2.24E+0	49.6	50.4	1.00E+0	1	1.21	
	electricity, medium voltage, at grid	US	0	kWh	1.23E-1	33.4	66.6	8.84E-3	1	1.21	
	tap water, at user	RER	0	kg	1.31E+0	98.8	1.2		1	1.21	
	sulphuric acid, liquid, at plant	RER	0	kg	7.45E-3	98.8	1.2		1	1.21	
	soda, powder, at plant	RER	0	kg	1.12E-2	98.8	1.2		1	1.21	
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	2.99E-3	98.8	1.2		1	1.21	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	2.99E-3	98.8	1.2		1	1.21	
	transport, tractor and trailer	CH	0	tkm	1.00E-2	98.8	1.2		1	2.05	(1,2,1,1,1,5); ecoinvent guidelines, standard distances
	ethanol fermentation plant	CH	1	unit	1.54E-10	50.1	49.9	5.30E-11	1	3.05	(1,2,1,1,1,5); etha+ project Alcosuisse, industrial data, cross checking with literature survey for US conditions
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	9.15E-4	41.6	58.4	4.96E-5	1	1.21	
	ethanol, 95% in H2O, from corn, at distillery	US	0	kg				1.00E+0	1	1.05	(1,1,1,1,1,1); Product, calculation
	transport, freight, rail	RER	0	tkm	1.48E-2	98.8	1.2		1	2.09	(4,5,na,na,na,na); ecoinvent guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	2.46E-3	98.8	1.2		1	2.09	
	transport, lorry 16t	RER	0	tkm	6.00E-2	98.8	1.2		1	2.09	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	7.74E-1	100.0	0.0		1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	3.07E+0	33.4	66.6	3.18E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

16.11 Ethanol from sweet sorghum, CN

16.11.1 System characterization

The system described in this paragraph includes the production of hydrated ethanol (95% vol.), bagasse, electricity and vinasse (stillage) from sweet sorghum in an integrated ethanol distillery, and the subsequent dehydration of the alcohol to ethanol 99.7% (wt.), in the Chinese context (Fig. 16.14).

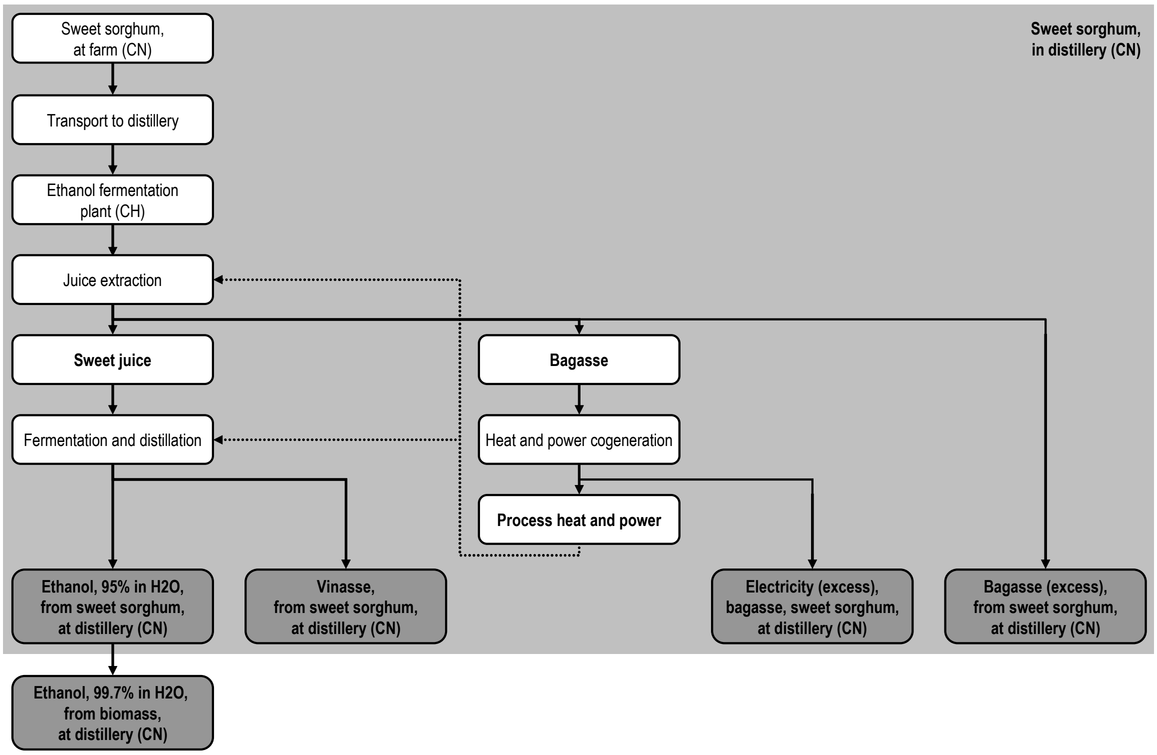


Fig. 16.14 Ethanol from sweet sorghum, CN: system definition and boundaries.

The description of the production process as well as LCI data of this process are adapted from the etha+ project of Alcosuisse (ENERS 2005; INTERIS 2002) and additional related references including (Woods 2000; LASEN 2004a).

On the basis of case study in (LASEN 2004a), the feed capacity considered for the distillery is taken as 1'270 kt/yr of sweet sorghum stems, which corresponds to a medium scale refinery in the Chinese context. The corresponding hydrated ethanol output is 74 kt per year (over a period of 100 days).

Because the sugar in sweet sorghum will deteriorate with storage, it must be extracted from the stems soon after the plant is harvested. Although this situation can be improved in cold climates where stalks may remain stored in the field for 4-5 months (Li 1997), it is assumed that sweet sorghum is processed immediately after harvesting, i.e. over 3-4 months (100 days).

The structure of sweet sorghum stems is quite similar to that of sugarcane, and hence, the processes of juice extraction are identical (Woods 2000). Like in Brazil, the technology for juice extraction involves a series of tandem roller mills with counter-current juice flow to leach solubles. Two primary streams exit the mill, namely (1) the sugar rich juice (or sweet juice), and (2) the fibre-rich bagasse. While the juice may be processed to raw sugar and molasses, only the conversion to ethanol is considered here (Fig. 16.14).

Just like for sugarcane, the energy used in the production of ethanol from sweet sorghum is completely produced by burning the bagasse. Like in the case of ethanol from sugar cane, excess bagasse amounts to 10% of the initial bagasse resulting from the extraction process when considering the process down to anhydrous ethanol (Woods 2000). The percentage reaches 14.5% when considering the production of only hydrated ethanol (the 4.5% corresponding to the fuel requirements for the dehydration stage).

The production of ethanol from sorghum sweet juice is analogous to that from molasses and the reader should refer to paragraph 16.5 for further details.

According to the composition of sweet sorghum and the data from Tab. 16.30, 1 ton of sweet sorghum stems (13% sugars, 11.7% fibres, 2.3% non-sugars and 73% water) results in:

- 58.2 kg of hydrated ethanol (95% wt., dry basis);
- 43.3 kWh of electricity (net production);
- 26.0 kg of excess bagasse (70.2% dry matter, 29.8% water);
- 768.4 kg of vinasse (15% dry matter, 85% water).

Allocation between the various outputs is performed, based on quoted CN market prices (Li et al. 2001) of anhydrous ethanol (3.5 RMBY/l), bagasse (60 RMBY/t) and electricity (580 RMBY/MWh). The vinasse is returned to sweet sorghum farmers as a fertilizer substitute and has no actual economic value (0 RMBY/t). The resulting allocation factors are indicated in Tab. 16.29.

Tab. 16.29 Allocation factors in the production of ethanol from sweet sorghum (CN).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Washing Cutting Diffusion	Anhydrous ethanol	91.3%	33.9%	4.8%	70.5%
	Excess bagasse	0.4%	12.1%	35.4%	4.8%
	Excess electricity	8.2%	8.0%	0.0%	0.0%
	Vinasse	0.0%	46.0%	59.8%	24.7%
Ethanol production					
Fermentation Distillation Dehydration	Anhydrous ethanol	100.0%	42.4%	7.4%	74.1%
	Excess bagasse	0.0%	0.0%	0.0%	0.0%
	Excess electricity	0.0%	0.0%	0.0%	0.0%
	Vinasse	0.0%	57.6%	92.6%	25.9%

The dehydration process of hydrated ethanol (95% wt.) to anhydrous ethanol (99.7% wt.) is performed by means of molecular sieves (see paragraph 16.7.2). The heat and electricity required for powering the dehydration are produced by burning the bagasse, just like in the upstream stages. The ratio of hydrated to anhydrous ethanol (wet basis) is 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

16.11.2 LCI of 'Sweet sorghum, in distillery, CN'

The production of sugar and ethanol from sugarcane in the Brazilian (BR) context is described in detail in paragraph 16.11.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

The data in Tab. 16.30 below presents the yields of ethanol from sugarcane, according to various literature references. The last three rows indicate the average values according to the quoted references and the values used in this study (on the basis of anhydrous and hydrated ethanol, respectively).

The ethanol yield considered here corresponds to the average value according to the quoted references.

Tab. 16.30 Literature review ethanol yields from sweet sorghum.

Reference	Year	Yields
		Sweet sorghum / CN Ethanol 99.7% wt. [kg/t]
Janssens 1992	1992	49.1
Worley et al. 1992	1992	59.5
Rains 1993	1993	62.4
El Bassam 1998	1998	57.1
Woods 2000	2000	52.4
Chiaramonti et al. 2002	2002	61.6
SORGHAL 2003	2003	55.5
ICRISAT 2004	2004	63.6
LASEN 2004a	2004	55.7
Raveendran 2004	2004	60.8
Raveendran 2004	2004	64.5
Average		**58.4**
This study (ethanol 99.7% wt. wet basis)		**58.4**
This study (ethanol 95% wt. wet basis)		**61.3**
This study (ethanol 95% wt. dry basis)		**58.2**

Unless stated otherwise, the data below is expressed per ton of sweet sorghum stems. Various references are compiled to establish the LCI of sugar and ethanol production from sweet sorghum, including (LASEN 2004a; ZAF 2002; ENERS 2005; INTERIS 2002; Woods 2000).

Sweet sorghum is transported to the distillery from nearby fields over an average distance of 20 km, of which 2 km are done by 16t lorry and 18 km by 32t lorry (Macedo 2004). Here, datasets for transport in the European context are used.

As far as energy is concerned, the respective consumptions of electricity and heat amount to 10.4 kWh and 1’405 MJ per ton of sugarcane, distributed over the stages of washing and extraction (2.9 kWh and 934 MJ), pressing of the bagasse (0.7 kWh and 234 MJ), and fermentation and distillation (6.8 kWh and 237 MJ). All the heat and power are produced locally by burning the pressed bagasse. Some excess electricity is also produced as a by-product of ethanol, which amounts to 43.3 kWh per ton of sweet sorghum. As indicated in paragraph 16.11, 85.5% of the bagasse are enough to supply energy to the entire process down to the distillation stage. Of the remaining 14.5% (26.0 kg per ton of sweet sorghum), 4.5% are used to power the dehydration, and 10% are sold on the market, as a by-product.

Raw materials used in the process include sulphuric acid (2.2 kg), various nutrients for bacterial growth in the form of ammonium sulphate and diammonium phosphate (0.29 kg N and 0.44 kg N respectively), and lubricating oil (0.01 kg). The delivery of raw materials is considered to be performed by road only (32t lorry), over an average distance of 650 km.

The consumption of water amounts to 856 kg per ton of sorghum stems. Most of the liquid effluents in the Chinese ethanol industry are returned to the fields as fertilizer complements or disposed of with no specific treatment in the proximate environment of the plant. In this case, the vinasse resulting from the distillation process is taken into account as by-product of ethanol, with a zero economic value.

The infrastructure of the ethanol distillery is described in the ‘ethanol fermentation plant’ dataset, with a production capacity of 90’000 t/yr (i.e. a feed capacity of 1’540 kt/yr of sweet sorghum) over a lifetime of 20 years. The actual infrastructure input (excluding the dehydration stage) is 2.81E-8 unit per ton of sweet sorghum.

Direct emissions of the complete process include carbon dioxide (CO_2) emissions from the fermentation process (59.2 kg, i.e. 0.972 kg per kg of hydrated ethanol or 1.020 kg per kg of anhydrous ethanol), and emissions from the combustion of the bagasse. Here again, the process ‘wood chips, burned in cogen 6400kWth’ is adapted and used to model the combustion. The properties and characteristics of pressed bagasse are given in Tab. 16.31 and compared with wood chips (u=40%).

Tab. 16.31 Characteristics and properties of pressed sorghum bagasse, compared with wood chips (u=40%).

	Sorghum bagasse		Wood chips, u=40%	
Water content	29.8	% w/w	28.6	% w/w
Dry matter content	70.2	% w/w	71.4	% w/w
Carbon content (dry matter basis)	44.3	% w/w	49.4	% w/w
Higher heating value	19.6	MJ/kg	20.2	MJ/kg
Lower heating value	13.8	MJ/kg	14.4	MJ/kg
Dry matter input	0.702	kg/kg	0.714	kg/kg
Carbon input	0.311	kg/kg	0.353	kg/kg
Energy input	13.766	MJ/kg	14.400	MJ/kg
Heat production	9.246	MJ/kg	11.045	MJ/kg
Electricity production	0.345	kWh/kg	0.331	kWh/kg

The process ‘wood chips, burned in cogen 6400kWth’ is adapted according to the same rules as in paragraph 16.7.2.

The two outputs of the MO-process 'sweet sorghum, in distillery' include:

- ethanol, 95% in H2O, from sweet sorghum, at distillery (dry basis): **58.2 kg/t sweet sorghum**;
- electricity, bagasse, sweet sorghum, at distillery: **43.3 kWh/t sugarcane**;
- bagasse, from sweet sorghum, at distillery: **26.0 kg/t sugarcane**;
- vinasse, from sweet sorghum, at distillery: **768.4 kg/t sugarcane**.

The economic allocation approach (paragraph 16.11, Tab. 16.29) is used, with factors of 92.1%, 7.5%, 0.4% and 0.0% respectively (applicable to common stages including the feedstock). The unit process raw data is indicated in Tab. 16.32.

16.11.3 LCI of 'Ethanol, 99.7% in H2O, from biomass, at distillation, CN'

The production of anhydrous ethanol 99.7% from hydrated ethanol 95% (dehydration) is described in detail in paragraph 16.11.1. This paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study. The unit process raw data is indicated in Tab. 16.32.

The ratio of hydrated to anhydrous ethanol (wet basis) is 1.05 kg hydrated ethanol per kg of anhydrous ethanol. On a dry matter basis, the input of hydrated ethanol 95% is 1 kg per kg of anhydrous ethanol 99.7%.

The energy use for the dehydration of anhydrous ethanol is taken from (ENERS 2005). The electricity and steam required amount to 23.8 kWh and 1520 MJ, respectively, per ton of anhydrous ethanol. The higher energy demand, compared to starch-crop processes (see paragraphs 16.8.3 and 16.10.3), is mainly due to the absence of stillage treatment, with which ethanol distillation and dehydration can be coupled. Like in the production of hydrated ethanol (paragraph 16.11.2), the heat and power are produced locally by burning the pressed bagasse (0.131 kg per ton of anhydrous ethanol). Again, the process 'wood chips, burned in cogen 6400kWth' is adapted and used to model the combustion. The properties and characteristics of pressed bagasse are given in Tab. 16.31.

Liquid effluents, corresponding to the water and so-called fusel oil removed from ethanol, amount to 49.5 l per ton of anhydrous ethanol and are eliminated in a wastewater treatment plant.

The infrastructure input (dehydration only) is 5.65E-8 unit per ton of anhydrous ethanol. Finally, waste heat to air (corresponding to the electricity consumption expressed in MJ) amount to 32 MJ.

Tab. 16.32 Unit process raw data of the dataset 'sweet sorghum, in distillery', CN.

	Name	Location	InfrastructureProcess	Unit	sweet sorghum, in distillery	ethanol, 95% in H2O, from sweet sorghum, at distillery	bagasse, from sweet sorghum, at distillery	electricity, bagasse, sweet sorghum, at distillery	vinasse, from sweet sorghum, at distillery	ethanol, 99.7% in H2O, from biomass, at distillation	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CN	CN	CN	CN	CN	CN			
	InfrastructureProcess				0	0	0	0	0	0			
	Unit				kg	kg	kg	kWh	kg	kg			
product	ethanol, 95% in H2O, from sweet sorghum, at distillery	CN	0	kg	5.82E-02	100.0							
product	bagasse, from sweet sorghum, at distillery	CN	0	kg	2.60E-02		100.0						
product	electricity, bagasse, sweet sorghum, at distillery	CN	0	kWh	4.33E-02			100.0					
product	vinasse, from sweet sorghum, at distillery	CN	0	kg	7.68E-01				100.0				
product	ethanol, 99.7% in H2O, from biomass, at distillation	CN	0	kg						1.00E+00			
resource, in air	Carbon dioxide, in air	-	-	kg	6.21E-2	0.0	44.5	0.0	55.5		1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
technosphere	sweet sorghum, at farm	CN	0	kg	1.00E+0	90.7	0.5	8.9	0.0		1	1.09	(2,1,1,1,1,3); Average ethanol yields in China, literature survey
	tap water, at user	RER	0	kg	8.56E-1	91.0	0.5	8.6	0.0		1	1.05	(1,1,1,1,1,1); Literature survey, industrial data
	sulphuric acid, liquid, at plant	RER	0	kg	2.20E-3	100.0	0.0	0.0	0.0		1	1.33	(2,4,1,3,3,5); etha+ project Alcosuisse, industrial data
	ammonium sulphate, as N, at regional storehouse	RER	0	kg	2.93E-4	100.0	0.0	0.0	0.0		1	1.33	
	diammonium phosphate, as N, at regional storehouse	RER	0	kg	4.39E-4	100.0	0.0	0.0	0.0		1	1.33	
	lubricating oil, at plant	RER	0	kg	1.85E-5	91.1	0.4	8.5	0.0	4.42E-6	1	1.33	(2,4,1,2,3,5); Compilation of data from sugarcane and sorghum milling, industrial data
	transport, lorry 32t	RER	0	tkm	1.65E-2	91.7	0.4	7.9	0.0		1	2.08	(2,4,1,5,1,5); Industrial data, for sweet sorghum delivery to sugar mill/ethanol plant; includes delivery of raw materials according to ecoinvent guidelines, adapted to Chinese conditions
	transport, lorry 16t	RER	0	tkm	1.27E-3	92.4	0.4	7.3	0.0		1	2.08	
	ethanol fermentation plant	CH	1	unit	2.91E-11	93.7	0.3	6.0	0.0	5.67E-11	1	3.06	(2,4,1,3,1,5); Calculation, according to feed capacity and lifetime of the plant
	ethanol, 95% in H2O, from sweet sorghum, at distillery	CN	0	kg						1.00E+0	1	1.24	(2,4,1,3,1,5); Calculation, according to ethanol content of input and ouput
	bagasse, from sweet sorghum, at distillery	CN	0	kg						1.31E-1	1	1.24	(2,4,1,3,1,5); Calculation, according to energy requirements for dehydration
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3						4.96E-5	1	1.35	(4,4,2,5,1,5); Calculation, according to mass balance
	ammonia, liquid, at regional storehouse	RER	0	kg	1.29E-8	92.1	0.4	7.5	0.0	1.10E-8	1	1.35	(4,4,2,5,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (pressed sorghum bagasse)
	chlorine, liquid, production mix, at plant	RER	0	kg	5.15E-7	92.1	0.4	7.5	0.0	4.42E-7	1	1.35	
	sodium chloride, powder, at plant	RER	0	kg	6.43E-6	92.1	0.4	7.5	0.0	5.52E-6	1	1.35	
	chemicals organic, at plant	GLO	0	kg	9.01E-6	92.1	0.4	7.5	0.0	7.73E-6	1	1.35	
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	5.15E-6	92.1	0.4	7.5	0.0	4.42E-6	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to landfarming	CH	0	kg	2.07E-4	92.1	0.4	7.5	0.0	1.78E-4	1	1.35	
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	5.15E-6	92.1	0.4	7.5	0.0	4.42E-6	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.07E-4	92.1	0.4	7.5	0.0	1.78E-4	1	1.35	
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	4.16E-4	92.1	0.4	7.5	0.0	3.57E-4	1	1.35	
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	1.24E-6	92.1	0.4	7.5	0.0	1.06E-6	1	1.35	
	water, decarbonised, at plant	RER	0	kg	1.24E-3	92.1	0.4	7.5	0.0	1.06E-3	1	1.35	
	cogen unit 6400kWth, wood burning, building	CH	1	unit	3.78E-10	92.1	0.4	7.5	0.0	3.24E-10	1	3.12	
	cogen unit 6400kWth, wood burning, common components for	CH	1	unit	1.51E-9	92.1	0.4	7.5	0.0	1.30E-9	1	3.12	
	cogen unit 6400kWth, wood burning, components for electricity only	CH	1	unit	1.51E-9	92.1	0.4	7.5	0.0	1.30E-9	1	3.12	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.09E-1	87.9	0.0	12.1	0.0	1.50E-1	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance (incl. carbon from the combustion of bagasse)
	Heat, waste	-	-	MJ	6.15E-1	92.1	0.4	7.5	0.0	1.78E+0	1	1.31	(2,3,1,1,3,5); ecoinvent guidelines, calculation from electricity consumption and
	Acetaldehyde	-	-	kg	9.57E-8	92.1	0.4	7.5	0.0	8.21E-8	1	1.65	(4,4,2,5,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (pressed sorghum bagasse)
	Ammonia	-	-	kg	2.73E-6	92.1	0.4	7.5	0.0	2.34E-6	1	1.41	
	Arsenic	-	-	kg	1.57E-9	92.1	0.4	7.5	0.0	1.35E-9	1	5.13	
	Benzene	-	-	kg	1.28E-6	92.1	0.4	7.5	0.0	1.10E-6	1	1.65	
	Benzene, ethyl-	-	-	kg	4.22E-8	92.1	0.4	7.5	0.0	3.62E-8	1	1.65	
	Benzene, hexachloro-	-	-	kg	1.01E-14	92.1	0.4	7.5	0.0	8.69E-15	1	3.12	
	Benzo(a)pyrene	-	-	kg	7.04E-10	92.1	0.4	7.5	0.0	6.04E-10	1	3.12	
	Bromine	-	-	kg	9.42E-8	92.1	0.4	7.5	0.0	8.08E-8	1	5.13	
	Cadmium	-	-	kg	1.10E-9	92.1	0.4	7.5	0.0	9.42E-10	1	5.13	
	Calcium	-	-	kg	9.18E-6	92.1	0.4	7.5	0.0	7.88E-6	1	5.13	
	Carbon monoxide, biogenic	-	-	kg	9.85E-6	92.1	0.4	7.5	0.0	8.45E-6	1	5.13	
	Chlorine	-	-	kg	2.83E-7	92.1	0.4	7.5	0.0	2.42E-7	1	1.65	
	Chromium	-	-	kg	6.22E-9	92.1	0.4	7.5	0.0	5.33E-9	1	5.13	
	Chromium VI	-	-	kg	6.28E-11	92.1	0.4	7.5	0.0	5.38E-11	1	5.13	
	Copper	-	-	kg	3.45E-8	92.1	0.4	7.5	0.0	2.96E-8	1	5.13	
	Dinitrogen monoxide	-	-	kg	3.61E-6	92.1	0.4	7.5	0.0	3.10E-6	1	1.65	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	4.36E-14	92.1	0.4	7.5	0.0	3.74E-14	1	3.12	
	Fluorine	-	-	kg	7.85E-8	92.1	0.4	7.5	0.0	6.73E-8	1	1.65	
	Formaldehyde	-	-	kg	1.83E-7	92.1	0.4	7.5	0.0	1.57E-7	1	1.65	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	1.28E-6	92.1	0.4	7.5	0.0	1.10E-6	1	1.65	
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	4.36E-6	92.1	0.4	7.5	0.0	3.74E-6	1	1.65	
	Lead	-	-	kg	3.91E-8	92.1	0.4	7.5	0.0	3.35E-8	1	5.13	
	Magnesium	-	-	kg	5.67E-7	92.1	0.4	7.5	0.0	4.86E-7	1	5.13	
	Manganese	-	-	kg	2.68E-7	92.1	0.4	7.5	0.0	2.30E-7	1	5.13	
	Mercury	-	-	kg	4.71E-10	92.1	0.4	7.5	0.0	4.04E-10	1	5.13	
	Methane, biogenic	-	-	kg	6.11E-7	92.1	0.4	7.5	0.0	5.24E-7	1	1.65	
	m-Xylene	-	-	kg	1.69E-7	92.1	0.4	7.5	0.0	1.45E-7	1	1.65	
	Nickel	-	-	kg	9.42E-9	92.1	0.4	7.5	0.0	8.08E-9	1	5.13	
	Nitrogen oxides	-	-	kg	1.38E-4	92.1	0.4	7.5	0.0	1.18E-4	1	1.65	
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	8.59E-7	92.1	0.4	7.5	0.0	7.36E-7	1	1.65	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	1.55E-8	92.1	0.4	7.5	0.0	1.33E-8	1	3.12	
	Particulates, < 2.5 um	-	-	kg	6.32E-5	92.1	0.4	7.5	0.0	5.42E-5	1	3.12	
	Phenol, pentachloro-	-	-	kg	1.14E-11	92.1	0.4	7.5	0.0	9.78E-12	1	1.65	
	Phosphorus	-	-	kg	4.71E-7	92.1	0.4	7.5	0.0	4.04E-7	1	1.65	
	Potassium	-	-	kg	3.67E-5	92.1	0.4	7.5	0.0	3.15E-5	1	5.13	
	Sodium	-	-	kg	2.04E-6	92.1	0.4	7.5	0.0	1.75E-6	1	5.13	
	Sulfur dioxide	-	-	kg	3.91E-6	92.1	0.4	7.5	0.0	3.35E-6	1	1.35	
	Toluene	-	-	kg	4.22E-7	92.1	0.4	7.5	0.0	3.62E-7	1	1.65	
	Zinc	-	-	kg	4.71E-7	92.1	0.4	7.5	0.0	4.04E-7	1	5.13	

16.12 Ethyl tert-butyl ether, RER

16.12.1 System characterization

The system described in this paragraph includes the production of ethyl tert-butyl ether (often referred to as ETBE), product of the reaction between ethanol (47% wt.) and isobutene (53% wt.), in the EU context (Fig. 16.15). Here, the dataset “naphtha, at refinery” is used a proxy dataset for isobutene[39]. In practise, however, there are three main types of etherification plants, based on raw material and processes, namely: (1) refineries/petrochemical plants, where isobutylene is produced in refinery catalytic crackers and in petrochemical ethylene plants; (2) merchant plants, where normal butane is isomerized to isobutane then dehydrogenated to isobutylene; and (3) TBA plants, where TBA (tertiary butyl alcohol) is dehydrated to isobutene. In the EU, refineries represent 64% of the capacity, while TBA and merchant plants reach 36% of the production capacity[40].

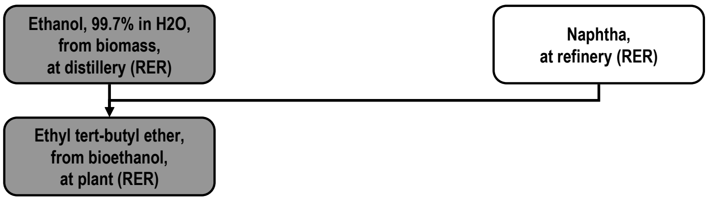


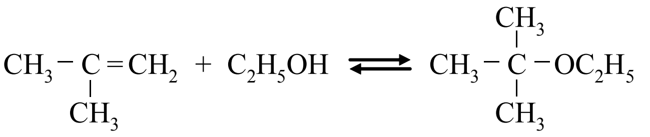
Fig. 16.15 Ethyl tert-butyl ether (ETBE), RER: system definition and boundaries.

The description of the production process and LCI data of this process are based on the IFP (Institut Français du pétrole) technology presented in (ADEME 2002; Patyk et al. 2000; Poitrat et al. 1998).

ETBE is synthesised by selective ethoxylation of isobutene with ethanol on an ion exchange resin. The IFP process is commercialized by Rohm & Haas or Dow Chemical.

In oil refineries and petrochemical plants, isobutene is obtained as a by-product of the catalytic cracking of naphtha, where naphtha is a fraction collected after the petroleum distillation between 70 and 220°C. The catalytic cracking consists in breaking the long carbon chains of hydrocarbon in order to obtain lighter products.

Ethanol is used in its anhydrous form (99.7% wt.) and modelled with the process ‘ethanol, 99.7% in H2O, from biomass, at distillation, RER’ (see paragraph 16.7.2). Additional rectification is not required but pre-treatment is included in the ETBE process, in order to eliminate basic compounds and cations, which have a negative effect on the catalyst. The reaction involved in the ETBE process is the following:



$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{C}}=CH_2 + C_2H_5OH \rightleftharpoons CH_3-\overset{\displaystyle CH_3}{\overset{|}{\underset{\displaystyle CH_3}{\underset{|}{C}}}}-OC_2H_5$$

[isobutene + ethanol $\rightleftharpoons$ ETBE]

Process conditions are such that the side reactions (not shown here) are kept to a minimum and the selectivity of isobutene and ethanol to ETBE is very high. The small amounts of by-products formed remain in the ETBE product, but do not adversely affect its quality.

The production of ETBE usually takes place in oil refineries, where most of the required process units already exist. This is the case in France and Spain, the two major producers of ETBE in the European Union.

16.12.2 LCI of ‘Ethyl tert-butyl ether, from bioethanol, at plant, RER’

The production of ethyl tert-butyl ether (ETBE) in the RER context is described in detail in paragraph 16.12.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in this study.

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[39] Personal communication of Michael Chudacoff and Michael Overcash, 18.02.2005.

[40] Personal communication of Walter Mirabella, Lyondell Chemical Europe Inc.

Inputs of ethanol (47% wt.) and isobutene (53% wt.) agree with the synthesis reaction involved (ethoxylation). As mentioned before, the dataset "naphtha, at refinery" is used a proxy dataset for isobutene. Heat, electricity and water inputs are derived from various literature references, and indicated in Tab. 16.33. The values used in this inventory correesponds to the average of the various values quoted in the literature.

Tab. 16.33 Energy and water inputs of ETBE production from various literature references.

Reference	Year	Energy inputs		Water inputs
		Heat, natural gas MJ/kg ETBE	**Electricity** kWh/kg ETBE	**Water** kg/kg ETBE
Poitrat et al. 1998	1998	2.344	0.014	0.620
LASEN 2000	2000	2.507	0.015	
Patyk et al. 2000	2000	4.924	0.014	
ADEME 2002	2002	1.700	0.053	
Average		**2.869**	**0.024**	**0.620**
This study (ETBE)		**2.869**	**0.024**	**0.620**

The water input is considered to leave the process as an effluent, and is eliminated in a wastewater treatment plant. Transport distances for the delivery of ethanol to the refinery are taken as 100 km by rail and 150 km by road (32 t lorry). The input of infrastructure is considered to be equal to that of 1 kg gasoline, i.e. 4.93E-11 unit per kg. Ethanol emissions to air are equal to 0.5% of the initial input, while emissions of waste heat correspond to the use of electricity (expressed in MJ).

The unit process raw data of 'ethyl tert-butyl ether, from bioethanol, at plant' is indicated in Tab. 16.34.

16.12.3 LCI of 'Petrol, 4% vol. ETBE additive, at refinery, RER'

The unit process 'petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery' described in this paragraph includes the production of a fuel blend consisting of 4% vol. ETBE (ethyl tert-butyl ether) and 96% vol. low-sulphur gasoline, at refinery (Fig. 16.16).

It is worth noting that, in the present life-cycle inventory, the use of standard (finished fuel grade) low-sulphur gasoline (as opposed to reformulated gasoline) is considered. However, the blending of ETBE with gasoline results in an improved octane index of the fuel blend (compared to conventional gasoline), and therefore, the generalization of ETBE incorporation into gasoline could allow refiners to lower the standards of gasoline used for blending with ETBE (and hence reduce the energy use and production costs).

Some refiners in the EU already use blendstocks for oxygenate blending (BOB) when mixing with ETBE is considered.

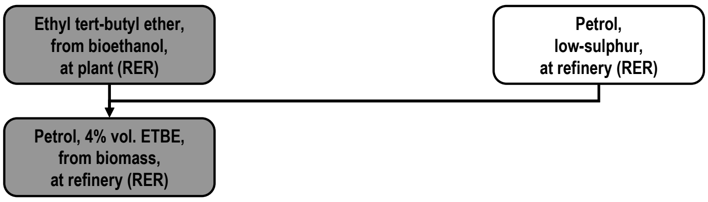

Fig. 16.16 Petrol, 4% vol. ETBE, RER: system definition and boundaries.

As opposed to the case of E5 and E85, the blending of ETBE and gasoline takes place at the refinery.

The incorporation rate of 4% (vol.) ETBE corresponds to the average incorporation rate of oxygenates (ETBE or MTBE) in gasoline in Switzerland.

Mass inputs are calculated according to the respective densities of ETBE (0.750 kg/l) and low-sulphur gasoline (0.750 kg/l). The unit process raw data of 'petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery ' is indicated in Tab. 16.34.

16.12.4 LCI of ‘Petrol, 15% vol. ETBE additive, at refinery, RER’

The unit process ‘petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery’ described in this paragraph includes the production of a fuel blend consisting of 15% vol. ETBE (ethyl tert-butyl ether) and 85% vol. low-sulphur gasoline, at refinery (Fig. 16.17). Again, standard (finished fuel grade) low-sulphur gasoline (as opposed to reformulated gasoline) is considered for the blending with ETBE. The remarks in the previous paragraph concerning the quality of gasoline apply here as well.

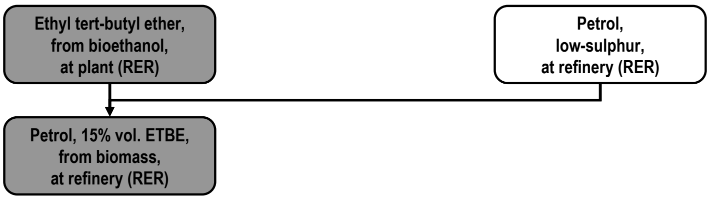

Fig. 16.17 Petrol, 15% vol. ETBE, RER: system definition and boundaries.

As opposed to the case of E5 and E85, the blending of ETBE and gasoline takes place at the refinery.

Mass inputs are calculated according to the respective densities of ETBE (0.750 kg/l) and low-sulphur gasoline (0.750 kg/l). The unit process raw data of 'petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery ' is indicated in Tab. 16.34.

Tab. 16.34 Unit process raw data of datasets relating to ETBE.

	Name	Location	InfrastructureProcess	Unit	ethyl tert-butyl ether, from bioethanol, at plant	petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery	petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery	UncertaintyType	StandardDeviation95%	GeneralComment
	Location InfrastructureProcess Unit				RER 0 kg	RER 0 kg	RER 0 kg			
product	ethyl tert-butyl ether, from bioethanol, at plant	RER	0	kg	1.00E+00					
product	petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery	RER	0	kg		1.00E+00				
product	petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery	RER	0	kg			1.00E+00			
technosphere	petrol, low-sulphur, at refinery	RER	0	kg		8.50E-1	9.60E-1	1	1.21	(1,2,1,1,1,5); Calculations, according to the incorporation rate of ETBE and the respective densities of ETBE (0.75 kg/l) and gasoline (0.75 kg/l)
	ethanol, 99.7% in H2O, from biomass, at distillation	RER	0	kg	4.70E-1			1	1.21	(1,2,1,1,1,5); Literature survey, ETBE synthesis chemical reaction (naphtha is used a a proxy dataset for isobutene)
	naphtha, at refinery	RER	0	kg	5.30E-1			1	1.21	
	ethyl tert-butyl ether, from bioethanol, at plant	RER	0	kg		1.50E-1	4.00E-2	1	1.05	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	2.87E+0			1	1.21	
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	2.40E-2			1	1.21	
	tap water, at user	RER	0	kg	6.20E-1			1	1.21	
	refinery	RER	1	unit	4.93E-11			1	3.05	(1,2,1,1,1,5); Calculations, according to production capacity of the refinery
	transport, freight, rail	RER	0	tkm	4.70E-2			1	2.09	(4,5,na,na,na,na); ecoinvent guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	7.05E-2			1	2.09	
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.20E-4			1	1.25	(2,4,1,3,3,3); Used water
emission air, high population density	Heat, waste	-	-	MJ	8.63E-2			1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Ethanol	-	-	kg	2.35E-4			1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties

16.13 Distribution of ethanol-based biofuels

The systems described in this paragraph include:

- the distribution in Switzerland of imported anhydrous ethanol (99.7% wt.);
- the distribution in Switzerland of gasoline ethanol blands (E5 and E85);

- the distribution in Switzerland of imported gasoline-ETBE fuel blends (15% and 4% vol.).

The transport distances involved in the various datasets are summarized in Tab. 16.35.

Tab. 16.35 Summary of the tranport distances involved in the distribution of ethanol-based biofuels.

Dataset	ethanol, 99.7% in H2O, from biomass, production US, at service station	ethanol, 99.7% in H2O, from biomass, production RER, at service station	ethanol, 99.7% in H2O, from biomass, production CN, at service station	petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station
Production country/region	US	RER	CN	RER	RER
Transport within producing country/region					
Train	1'700		850		
Lorry 32t	100		150		
Transport overseas	7'000		23'000		
Transport within the EU to Swiss border					
Train		650	500	165	165
Lorry 32t		150			
Barge	840				
Transport within Switzerland					
Train	100	100	100	100	100
Lorry 28t	150	150	150	150	150
Total distance	**9'890**	**1'050**	**24'750**	**415**	**415**

For reasons of consistency with other datasets relating to the distribution of fuels (e.g. gasoline, diesel), the datasets described in this paragraph are based on the existing dataset 'petrol, unleaded, at regional storage' (Jungbluth 2004). Operation of storage tanks and petrol stations are taken into account. Emissions from the treatment of effluents are included. Fugitive emissions (0.05% wt.) are adapted to the specific nature of the various fuels concerned. Emissions from car-washing at petrol stations however are excluded.

Due to a lack of information about actual distances, standard distances are used for the distribution from the Swiss border to service stations (see Part I of this report). These include 100 km by train and 150 km by 28t lorry.

Depending on the policy of the fuel distributors, the formulation of E5 and E85 may be performed at the oil refinery or directly at the service station or regional storage before distribution to the end-user. The preferred strategy in Switzerland, according to Alcosuisse[41], consists in the direct blending of ethanol and gasoline as far downstream as possible in the distribution chain. The two components are hence considered to be mixed at the service station.

16.13.1 LCI of 'Ethanol, 99.7% in H2O, production RER, at service station, CH'

The unit process 'ethanol, 99.7% in H2O, from biomass, production RER, at service station' envisages the import of anhydrous ethanol from the European Union, and the distribution to the end-user at service stations in Switzerland.

Ethanol is supposed to be produced from rye in the RER context, and is delivered to Geneva or Basel. The distance from the production site to the Swiss border is considered to be 650 km by rail and 150 km by 32t lorry. Standard distances are used for the distribution within Switzerland.

The unit process raw data of 'ethanol, 99.7% in H2O, from biomass, production RER, at service station' is indicated in Tab. 16.36.

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[41] Personal communication of M. Pierre Schaller (Alcosuisse), 2006.

16.13.2 LCI of ‘Ethanol, 99.7% in H2O, production US, at service station, CH’

The unit process 'ethanol, 99.7% in H2O, from biomass, production US, at service station' envisages the import of anhydrous ethanol from the United States, and the distribution to the end-user at service stations in Switzerland.

Ethanol is supposed to be produced from corn in the US context. Ethanol is first transported within the US from the mid-West (where ethanol plants are concentrated, Fig. 16.18) to the East Coast (1’700 km rail and 100 km road), and then overseas to Rotterdam harbour by tanker (7’000 km). Upon arrival in Europe, the ethanol is loaded on barges and delivered to the Swiss border in Basel (840 km). Standard distances are used for the distribution within Switzerland.

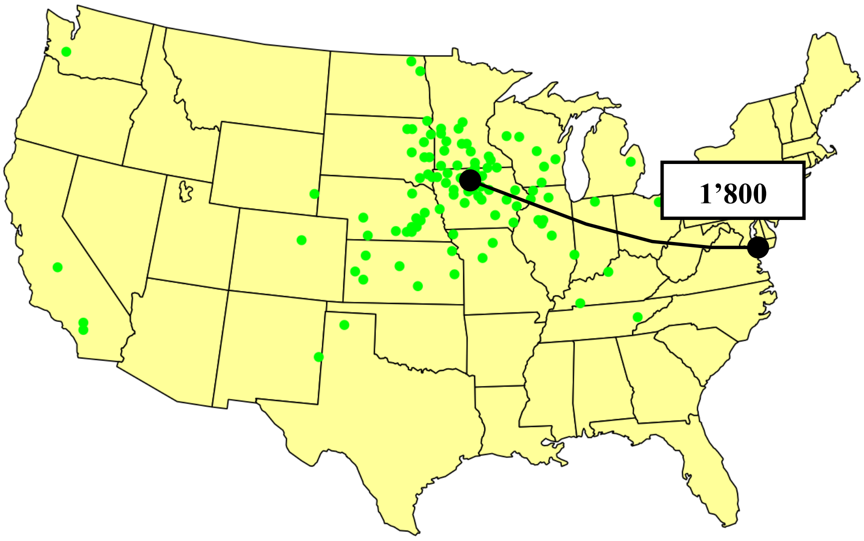


Fig. 16.18 Location of ethanol plants in the US (adapted from Renewable Fuels Association, 2006).

The unit process raw data of 'ethanol, 99.7% in H2O, from biomass, production US, at service station' is indicated in Tab. 16.36.

16.13.3 LCI of ‘Ethanol, 99.7% in H2O, production CN, at service station, CH’

The unit process 'ethanol, 99.7% in H2O, from biomass, production CN, at service station' envisages the import of anhydrous ethanol from China, and the distribution to the end-user at service stations in Switzerland.

Ethanol is supposed to be produced from sweet sorghum in the CN context. Ethanol is first transported within China to a harbour on the East or South coast (850 km rail and 150 km road), and then overseas to Marseille harbour by tanker (23’000 km via the Suez Canal). Upon arrival in Europe, the ethanol is loaded on trains and delivered to the Swiss border in Geneva (500 km). Standard distances are used for the distribution within Switzerland.

The unit process raw data of 'ethanol, 99.7% in H2O, from biomass, production CN, at service station' is indicated in Tab. 16.36.

Tab. 16.36 Unit process raw data of datasets relating to imported ethanol, CH.

	Name	Location	InfrastructureProcess	Unit	ethanol, 99.7% in H2O, from biomass, production US, at service station	ethanol, 99.7% in H2O, from biomass, production RER, at service station	ethanol, 99.7% in H2O, from biomass, production CN, at service station	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	ethanol, 99.7% in H2O, from biomass, production US, at service station	CH	0	kg	1.00E+00					
product	ethanol, 99.7% in H2O, from biomass, production RER, at service station	CH	0	kg		1.00E+00				
product	ethanol, 99.7% in H2O, from biomass, production CN, at service station	CH	0	kg			1.00E+00			
technosphere	ethanol, 99.7% in H2O, from biomass, at distillation	US	0	kg	1.00E+0			1	1.05	(1,1,1,1,1,1); Product plus losses
	ethanol, 99.7% in H2O, from biomass, at distillation	RER	0	kg		1.00E+0		1	1.05	
	ethanol, 99.7% in H2O, from biomass, at distillation	CN	0	kg			1.00E+0	1	1.05	
	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	6.70E-3	6.70E-3	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage and filling station)
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	6.21E-4	6.21E-4	1	1.25	
	transport, freight, rail	RER	0	tkm	1.70E+0	6.50E-1	1.35E+0	1	2.09	(4,5,na,na,na,na); Assumption, standard distances
	transport, lorry 32t	RER	0	tkm	1.00E-1	1.50E-1	1.50E-1	1	2.09	
	transport, freight, rail	CH	0	tkm	1.00E-1	1.00E-1	1.00E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.50E-1	1.50E-1	1.50E-1	1	2.09	
	transport, transoceanic tanker	OCE	0	tkm	7.00E+0	0	2.30E+1	1	2.09	(4,5,na,na,na,na); Assumption, distance to Rotterdam (NL) or Marseille (FR)
	transport, barge tanker	RER	0	tkm	8.40E-1	0	0	1	2.09	(4,5,na,na,na,na); Rotterdam to Basel
	regional distribution, oil products	RER	1	unit	2.62E-10	2.62E-10	2.62E-10	1	3.06	(3,na,1,3,3,na); Average data for petrol station
	tap water, at user	CH	0	kg	6.89E-4	6.89E-4	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for petrol distribution
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1.68E-4	1.68E-4	1	1.27	(2,4,3,3,3,3); Sludge from storage, environmental report and literature
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	6.27E-6	6.27E-6	1	1.25	(2,4,1,3,3,3); Environmental report for wastes
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	7.50E-5	7.50E-5	1	1.40	(4,5,3,3,3,na); Treatment of rainwater with pollutants
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	6.89E-7	6.89E-7	1	1.25	(2,4,1,3,3,3); Used water
emission air, high population density	Heat, waste	-	-	MJ	2.41E-2	2.41E-2	2.41E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Ethanol	-	-	kg	5.00E-4	5.00E-4	5.00E-4	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties

16.13.4 LCI of ‘Petrol, 5% vol. ethanol, from biomass, at service station, CH’

The unit process ‘petrol, 5% vol. ethanol, from biomass, at service station’ described in this paragraph includes the distribution of a fuel blend consisting of 5% vol. ethanol from biomass and 95% vol. low-sulphur gasoline (E5) to the end user, at filling stations (Fig. 16.19). Mixing is supposed to be performed at the filling station directly (splash blending).

It is worth noting that, in the present life-cycle inventory, the use of standard (finished fuel grade) low-sulphur gasoline (as opposed to reformulated gasoline) is considered. The resulting increase in the vapour pressure of the fuel blend (compared to conventional gasoline), often referred to as the RVP effect, is not taken into account. In summer conditions, indeed, the vapour pressure of E5 exceeds the RVP limit as specified in the Swiss Norm SN EN 228 (on the quality of gasoline). In Switzerland, the commercialization of E5 benefits from an exception by the Swiss authorities, until the probable revision of the norm.

In addition, the blending of ethanol with gasoline results in an improved octane index of the fuel blend (compared to conventional gasoline). The generalization of ethanol incorporation into gasoline could therefore, in theory, could allow refiners to lower the standards of gasoline used for blending with ethanol (and hence reduce the energy use and production costs).

As long as the use of E5 is not generalized, however, conventional gasoline (finished fuel grade) is very much likely to remain the component of choice for the blending with ethanol in the case of splash blending.

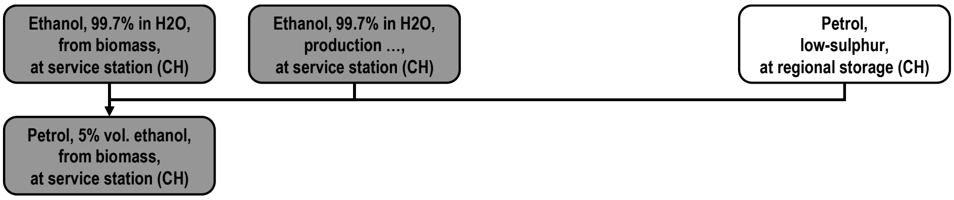


Fig. 16.19 E5 (5% vol. ethanol mixed with 95% vol. gasoline): system definition and boundaries.

Ethanol is partly produced in CH (25%) according to the production mix, and partly imported from BR (37.5%) and RER (37.5%). LCI data includes the distribution to the final consumer (service station) including all necessary transports.

Mass inputs are calculated according to the respective densities of bioethanol (0.795 kg/l) and gasoline (0.750 kg/l). The unit process raw data of 'petrol, 5% vol. ethanol, from biomass, at service station' is indicated in Tab. 16.37.

16.13.5 LCI of ‘Petrol, 85% vol. ethanol, from biomass, at service station, CH’

The unit process ‘petrol, 85% vol. ethanol, from biomass, at service station’ described in this paragraph includes the distribution of a fuel blend consisting of 85% vol. ethanol from biomass and 15% vol. low-sulphur gasoline (E85) to the end user, at filling stations (Fig. 16.20). Mixing is supposed to be performed at the filling station directly (splash blending).

As in the case of E5, the use of standard (finished fuel grade) low-sulphur gasoline (as opposed to reformulated gasoline) is considered.

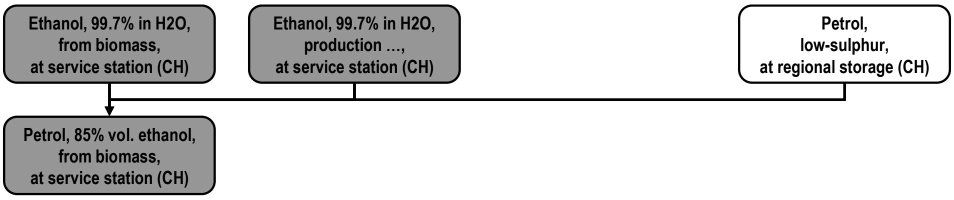


Fig. 16.20 E85 (85% vol. ethanol mixed with 15% vol. gasoline): system definition and boundaries.

Like in the case of E5 (and although the market for E85 is likely to be more limited), ethanol is partly produced in CH (25%) according to the production mix, and partly imported from BR (37.5%) and RER (37.5%). LCI data includes the distribution to the final consumer (service station) including all necessary transports.

Mass inputs are calculated according to the respective densities of bioethanol (0.795 kg/l) and gasoline (0.750 kg/l). The unit process raw data of 'petrol, 85% vol. ethanol, from biomass, at service station' is indicated in Tab. 16.37.

16.13.6 LCI of ‘Petrol, 4% vol. ETBE, production RER, at service ‘station, CH’

The unit process 'petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station' includes the production of gasoline with 4% vol. ETBE in the European context, and the distribution to the end-user at service stations in Switzerland.

The gasoline-ETBE blend is supposed to be imported from the refinery in Feysin (France). Transport distance is 150 km by train to the Swiss border in Geneva. Standard distances are used for the distribution within Switzerland.

The unit process raw data of 'petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station' is indicated in Tab. 16.37.

16.13.7 LCI of ‘Petrol, 15% vol. ETBE, production RER, at service ‘station, CH’

The unit process 'petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station' includes the production of gasoline with 15% vol. ETBE in the European context, and the distribution to the end-user at service stations in Switzerland.

Like in the previous paragraph, the gasoline-ETBE blend is supposed to be imported from the refinery in Feysin (France). Transport distance is 150 km by train to the Swiss border in Geneva. Standard distances are used for the distribution within Switzerland.

The unit process raw data of 'petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station' is indicated in Tab. 16.37.

Tab. 16.37 Unit process raw data of the datasets relating to the distribution of ethanol-based fuel blends, CH.

	Name	Location	InfrastructureProcess	Unit	petrol, 5% vol. ethanol, from biomass, at service station	petrol, 85% vol. ethanol, from biomass, at service station	petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	petrol, 5% vol. ethanol, from biomass, at service station	CH	0	kg	1.00E+00						
product	petrol, 85% vol. ethanol, from biomass, at service station	CH	0	kg		1.00E+00					
product	petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service	CH	0	kg			1.00E+00				
product	petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service	CH	0	kg				1.00E+00			
technosphere	petrol, low-sulphur, at regional storage	CH	0	kg	9.47E-1	1.43E-1			1	1.21	(1,2,1,1,1,5);
	ethanol, 99.7% in H2O, from biomass, production RER, at service station	CH	0	kg	1.98E-2	3.21E-1			1	1.21	(1,2,1,1,1,5); Calculations, according to the assumed ethanol
	ethanol, 99.7% in H2O, from biomass, production BR, at service station	CH	0	kg	1.98E-2	3.21E-1			1	1.21	
	ethanol, 99.7% in H2O, from biomass, at service station	CH	0	kg	1.32E-2	2.14E-1			1	1.21	
	petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery	RER	0	kg			1.00E+0		1	1.05	(1,1,1,1,1,1); Product plus losses
	petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery	RER	0	kg				1.00E+0	1	1.05	
	electricity, low voltage, at grid	CH	0	kWh			6.70E-3	6.70E-3	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage and filling station)
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ			6.21E-4	6.21E-4	1	1.25	
	transport, freight, rail	RER	0	tkm			1.65E-1	1.65E-1	1	2.09	(4,5,na,na,na,na); Assumption, standard distances
	transport, freight, rail	CH	0	tkm			1.00E-1	1.00E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm			1.50E-1	1.50E-1	1	2.09	
	regional distribution, oil products	RER	1	unit			2.62E-10	2.62E-10	1	3.06	(3,na,1,3,3,na); Average data for petrol station
	tap water, at user	CH	0	kg			6.89E-4	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for petrol distribution
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg			1.68E-4	1.68E-4	1	1.27	(2,4,3,3,3,3); Sludge from storage, environmental report and
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg			6.27E-6	6.27E-6	1	1.25	(2,4,1,3,3,3); Environmental report for wastes
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3			7.50E-5	7.50E-5	1	1.40	(4,5,3,3,3,na); Treatment of rainwater with pollutants
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3			6.89E-7	6.89E-7	1	1.25	(2,4,1,3,3,3); Used water
emission air, high population density	Heat, waste	-	-	MJ			2.41E-2	2.41E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity
	Ethanol	-	-	kg			3.53E-5	9.40E-6	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
	Benzene	-	-	kg			4.55E-6	4.81E-6	1	1.70	
	Benzene, ethyl-	-	-	kg			9.57E-6	1.01E-5	1	1.70	
	Hexane	-	-	kg			5.92E-6	6.25E-6	1	1.70	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg			2.49E-4	2.63E-4	1	1.70	
	Hydrocarbons, aliphatic, unsaturated	-	-	kg			4.55E-5	4.81E-5	1	1.70	
	Hydrocarbons, aromatic	-	-	kg			4.55E-5	4.81E-5	1	1.70	
	Methane, fossil	-	-	kg			1.37E-7	1.44E-7	1	1.70	
	t-Butyl methyl ether	-	-	kg			2.28E-5	2.40E-5	1	1.70	
	Toluene	-	-	kg			2.28E-5	2.40E-5	1	1.70	
	Xylene	-	-	kg			5.01E-5	5.29E-5	1	1.70	

16.14 Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation in all the datasets. Apart from the inventory of the sugar refinery (paragraph 16.5.2), the inventories presented in this chapter are based mostly on industrial data from trusted sources and are considered to be reliable.

Most datasets relating to ethanol production in this chapter are MO-processes with input data referring to one unit of feedstock. The comparison of energy and raw materials inputs (between various ethanol production pathways) is therefore not quite straight-forward. The data in Tab. 16.38 presents a summary of the most significant inputs on a “per kg of ethanol (95% wt.)” basis.

The selected inputs for the comparison between the various pathways include heat, electricity, water, as well as chemicals and nutrients. The data takes into account the allocation to ethanol.

Tab. 16.38 Summary table of the various ethanol production pathways (per kg of ethanol 95% wt.).

		Sugar beet molasses	Potatoes	Wood	Rye	Sugarcane molasses	Corn	Sweet sorghum
Country		CH	CH	CH	RER	BR	US	CN
Chapter		1.5	1.6	1.7	1.8	1.9	1.10	1.11
Inventory data								
(with allocation)								
Heat, natural gas	MJ	2.8741	5.8056	-	3.4826	-	3.4490	-
Electricity	kWh	0.2085	0.1733	-	0.1311	-	0.1276	-
Water	kg	7.2270	0.9726	7.6240	3.9702	20.1520	4.0129	12.7105
Sulphuric acid	kg	0.0339	0.0171	0.0785	0.0237	0.0537	0.0228	0.0359
Soda powder	kg	-	0.0396	-	0.0355	0.0031	0.0343	-
Ammonia	kg	-	-	0.0626	-	-	-	-
Ammonium sulphate	kg	0.0045	0.0104	0.0011	0.0095	0.0084	0.0092	0.0048
Diammonium phosphate	kg	0.0068	0.0104	0.0016	0.0095	0.0126	0.0092	0.0072
Magnesium sulphate	kg	-	-	0.0005	-	-	-	-
Maize starch	kg	-	-	0.0251	-	-	-	-
Quicklime	kg	-	-	0.0305	-	-	-	-

16.15 Cumulative results and interpretation

16.15.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in (Frischknecht et al. 2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

16.15.2 Selected LCI results and cumulative energy demand

Tab. 16.39 shows selected LCI results (including greenhouse gas emissions) and the cumulative energy demand of vegetable oil methyl ester datasets.

Tab. 16.39 Selected LCI results and the cumulative energy demand of ethanol 95% in H_2O

		Name		ethanol, 95% in H2O, from sugar beet molasses, at distillery	ethanol, 95% in H2O, from potatoes, at distillery	ethanol, 95% in H2O, from wood, at distillery	ethanol, 95% in H2O, from rye, at distillery	ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery	ethanol, 95% in H2O, from corn, at distillery	ethanol, 95% in H2O, from sweet sorghum, at distillery
		Location		CH	CH	CH	RER	BR	US	CN
		Unit	Unit	kg	kg	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0	0	0
LCIA results										
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	9.3	20.8	6.8	19.6	4.7	18.9	5.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.7	3.2	0.5	2.3	0.5	2.1	1.8
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.1	1.3	0.2	0.5	0.1	0.5	0.5
	cumulative energy demand	renewable energy resources, wind, solar,	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	18.3	57.9	76.1	47.2	59.1	52.6	70.8
LCI results										
resource	Land occupation	total	m2a	8.0E-1	4.7E+0	4.2E+0	8.2E+0	1.6E+0	2.4E+0	1.1E+0
air	Carbon dioxide, fossil	total	kg	5.4E-1	1.2E+0	4.0E-1	1.1E+0	2.7E-1	1.1E+0	3.1E-1
air	NMVOC	total	kg	3.9E-4	1.4E-3	8.2E-4	1.0E-3	4.7E-4	9.6E-4	5.6E-4
air	Nitrogen oxides	total	kg	1.7E-3	6.5E-3	2.8E-3	6.0E-3	3.8E-3	4.3E-3	4.2E-3
air	Sulphur dioxide	total	kg	1.0E-3	2.0E-3	1.8E-3	3.3E-3	1.8E-3	2.7E-3	1.5E-3
air	Particulates, < 2.5 um	total	kg	1.8E-4	6.0E-4	2.9E-4	5.9E-4	1.2E-3	3.7E-4	1.2E-3
water	BOD	total	kg	7.4E-4	2.7E-3	1.2E-3	2.2E-3	8.3E-4	2.5E-3	9.5E-4
soil	Cadmium	total	kg	-3.2E-7	3.9E-7	4.5E-8	2.9E-6	3.9E-7	1.1E-7	-2.9E-7
Further LCI results										
air	Carbon dioxide, biogenic	total	kg	-1.9E+0	-1.9E+0	-1.9E+0	-1.9E+0	-2.5E+0	-1.9E+0	-1.9E+0
air	Carbon dioxide, land transformation	low population density	kg	3.6E-6	1.0E-5	1.7E-6	1.3E-4	2.3E-5	5.4E-5	2.4E-5
air	Methane, biogenic	total	kg	1.0E-5	5.4E-6	1.4E-5	7.3E-6	3.4E-3	5.7E-6	1.6E-5
air	Carbon monoxide, biogenic	total	kg	8.8E-5	2.2E-4	2.2E-4	7.0E-5	3.6E-1	3.9E-5	1.9E-4
	biogenic C-content in product	calculated	kg	0.522	0.522	0.522	0.523	0.522	0.523	0.521
	CO2, biogenic-content in product	calculated	kg	1.913	1.913	1.913	1.918	1.913	1.918	1.909
	C-content in product	according to product properties -->	kg	0.522	0.522	0.522	0.522	0.522	0.522	0.522

The main results of this quoted in Tab. 16.39, more particularly the cumulative energy demand as well as greenhouse gas (GHG) emissions of ethanol 95% in H_2O (at distillery) are compared with literature data.

In the literature, the cumulative energy demand (CED) is often expressed as the so-called "energy ratio", i.e. the ratio of the energy produced in the form of biofuel to the equivalent non renewable primary energy consumed (i.e. energy out/energy in). This energy ratio is therefore equal to the ratio of the higher heating value (HHV) to the non renewable CED.

The cumulative energy demand (CED) is here limited to non renewable energy (i.e. fossil and nuclear). The "energy ratio" for the datasets in this study is calculated as the HHV of ethanol 95% (26.8 MJ/kg, 100% basis) to the CED (in MJ/kg).

The comparison is presented in Tab. 16.40

Tab. 16.40 Comparison of cumulative (non renewable) energy demand and CO_2 emissions of ethanol 95% (as described in this study) with literature data.

Literature reference	Year	Feedstock	Country	E_{out}/E_{in} MJ/MJ	CED MJ/kg	IPCC 100a kg/kg	CO_2 kg/kg
(ADEME 1996)	1996	Sugarbeet	FR	1.18	22.7	0.56	
(LASEN 2000)	2000	Sugarbeet	CH	2.50	10.7	0.70	
(LBST 2002)	2002	Sugarbeet	RER	1.65	16.2	1.02	
(ADEME 2002)	2002	Sugarbeet	FR	2.05	13.1	0.90	
(Woods 2003)	2003	Sugarbeet	UK	1.75	15.3	2.10	
(Elsayed 2003)	2003	Sugarbeet	UK	2.00	13.4	1.07	
(Edwards 2006)	2006	Sugarbeet	RER	1.65	16.2	1.02	
(ENERS 2006)	2006	Sugarbeet	CH	1.53	17.5	1.12	
(LASEN 2004)	2004	Sugarbeet molasses	CH	1.47	18.2	1.27	
(ENERS 2006)	2006	Sugarbeet molasses	CH	2.00	13.4	0.77	
This study	2006	Sugarbeet molasses	CH	2.23	12.0	0.78	0.54
(Lorrenz 1995)	1995	Wood	US	2.62	10.2		
(LASEN 2000)	2000	Grass	CH	2.50	10.7	0.65	
(LBST 2002)	2002	Wood	RER	4.30	6.2	0.39	
(LASEN 2002)	2002	Wood	CH	2.04	13.1	0.75	
(LASEN 2002)	2002	Grass	CH	1.88	14.3	0.79	
(Woods 2003)	2003	Wood	UK	1.80	14.9	0.57	
(Elsayed 2003)	2003	Straw	UK	5.60	4.8	0.35	
(Pimentel 2005)	2005	Grass	US	0.68	39.7		
(ENERS 2006)	2006	Wood	CH	3.46	7.7	0.33	
(ENERS 2006)	2006	Straw	CH	3.37	8.0	0.51	
(ENERS 2006)	2006	Grass	CH	2.28	11.8	1.01	
This study	2006	Wood	CH	3.67	7.3	0.55	0.40
(ADEME 2002)	2002	Wheat	FR	2.05	13.1	0.92	
(Woods 2003)	2003	Wheat	UK	2.25	11.9	1.82	
(Elsayed 2003)	2003	Wheat	UK	2.20	12.2	0.78	
(LASEN 2004)	2004	Wheat	CH	1.05	25.5	1.77	
(ENERS 2006)	2006	Wheat	CH	1.42	18.9	1.43	
(ENERS 2006)	2006	Rye	CH	1.72	15.6	1.03	
This study	2006	Rye	RER	1.22	21.9	2.12	1.15
(LASEN 2004)	2004	Potatoes	CH	0.87	30.8	2.03	
(ENERS 2006)	2006	Potatoes	CH	1.08	24.8	1.60	
This study	2006	Potatoes	CH	1.11	24.0	2.30	1.22
(Ho 1989)	1989	Corn	US	0.95	26.8		
(Pimentel 1991)	1991	Corn	US	0.69	36.9		
(Marland 1991)	1991	Corn	US	1.28	19.9		
(Keeney 1992)	1992	Corn	US	0.92	27.7		
(Morris 1992)	1992	Corn	US	1.51	16.9		
(Shapouri 1995)	1995	Corn	US	1.30	19.6		
(Lorenz 1995)	1995	Corn	US	1.38	18.4		
(Levelton 1999)	1999	Corn	US	1.60	15.9		
(Wang 2002)	2002	Corn	US	1.42	17.9		
(Andress 2002)	2002	Corn	US	1.31	19.4		
(Shapouri 2002)	2002	Corn	US	1.37	18.6		
(Graboski 2002)	2002	Corn	US	1.22	20.9		
(Patzek 2003)	2003	Corn	US	0.99	25.7		
(Shapouri 2004)	2004	Corn	US	1.67	15.2		
(Pimentel 2005)	2005	Corn	US	0.78	32.6		
(ENERS 2006)	2006	Corn (grains)	CH	0.76	33.5	2.14	
(ENERS 2006)	2006	Corn (ensiled)	CH	1.07	23.8	1.41	
This study	2006	Corn	US	1.27	21.0	1.87	1.15
(Macedo 2004)	2004	Sugarcane	BR	8.20	3.1	0.31	
(ENERS 2006)	2006	Sugarcane	BR	4.33	5.9	0.00	
(ENERS 2006)	2006	Sugarcane molasses	BR	4.11	6.2	0.10	
This study	2006	Sugarcane molasses	BR	5.21	5.1	0.42	0.27
This study	2006	Sweet sorghum	CN	3.74	7.2	0.60	0.31

One should be aware, though, that the data from the literature most often (if not always) refers to anhydrous ethanol (99.7% wt. wet basis), whereas the data from this study refers to hydrated ethanol (95% wt.) and is given on a dry basis (i.e. 1 kg ethanol dry basis is equal to 1.05 kg ethanol 95% wet basis). Because these two facts tend to compensate each others, the data in Fig. 16.21 is left as such, i.e. no correction is applied.

In Tab. 16.40, the impact according to IPCC 100a does not include CO_2 emissions from land transformation (see Tab. 16.39). The data presented in Tab. 16.40 are illustrated in Fig. 16.21 (Cumulative energy demand) and Fig. 16.22 (CO_2 emissions).

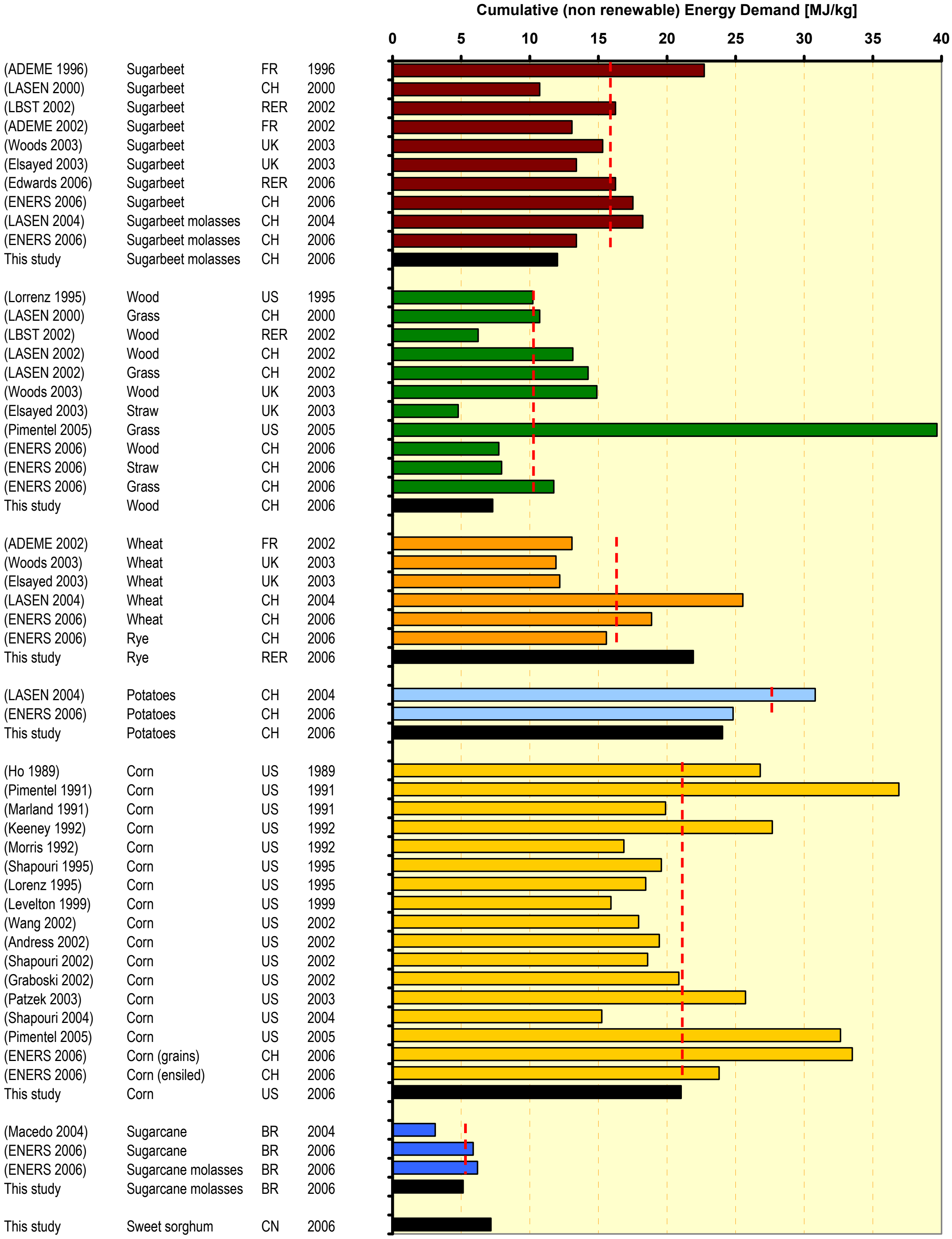


Fig. 16.21 Comparison of CED (non renewable) results with literature data.

The dotted line indicates the average of the literature data considered in the comparison. The results in Fig. 16.21 show that the CED obtained for the datasets in this study is a little lower than the average (apart from the case of ethanol from rye, RER), but seem coherent with literature references.

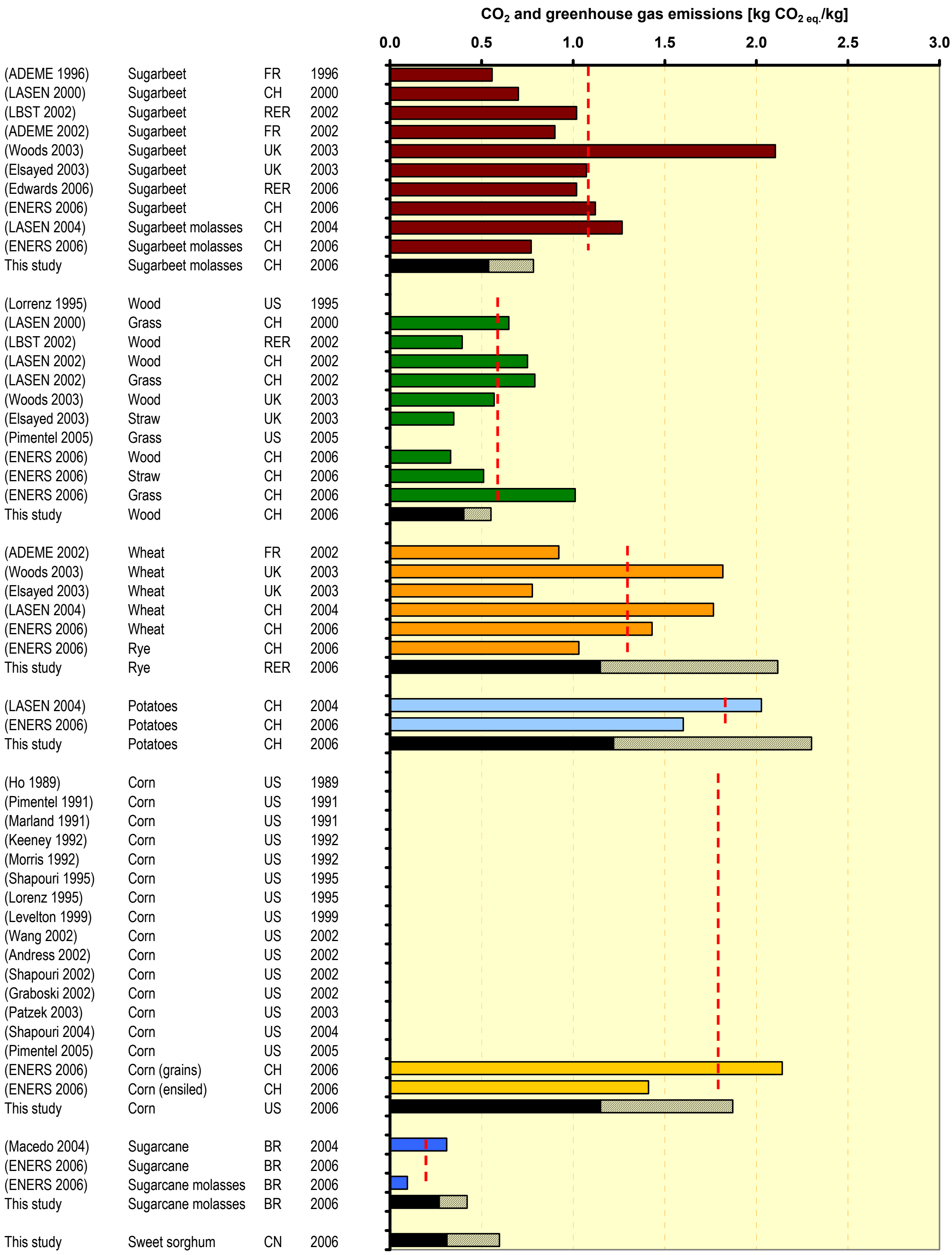


Fig. 16.22 Comparison of CO$_2$ emissions with literature data.

In **Fig. 16.22**, most of the literature data refers to total greenhouse gas emissions (although some of the references do not indicate it precisely). Concerning the results of this study, both CO$_2$ only (solid) and total GHG (striped) emissions are shown.

Again, it proved difficult to figure out when literature data were refering to CO_2 only or global GHG emissions, and this may be the cause of significant differences. CO_2 of biogenic nature (captured and emitted) is not included (i.e. considered to have a zero global warming potential) in the data presented in **Fig. 16.22**.

It is very difficult to explain the differences as many factors can influence the results (e.g. inventory data, agricultural practise, technology, plant size, methodology, allocation method, structure and efficiency of energy systems, etc.). On a general basis, the results seem coherent with literature data.

16.16 Conclusions

The production of fuel ethanol and related datasets is largely determined by the impact of the agricultural phase. Because of the allocation issue, only the carbon balance is satisfied within these datasets. Because allocation, indeed, is done according to the respective economic values of the by-products, it is not possible to satisfy both the carbon and the energy balances. The deviation in terms of energy balance, however, is relatively small and should not be a problem at all when evaluating the environmental impacts.

The production of fuel ethanol outside of the EU is here limited to Brazil, the US and China, currently the largest producers together with the EU as a whole. With the growing interest in biofuels in industrialized countries and the expected development of international commerce, more and more tropical countries with favourable climatic and structural conditions are embarking on large scale biofuels programs. In the near future, it is likely that the number of “overseas” ethanol producers will grow, representing as many potential suppliers of EU countries and possibly Switzerland. Future upgrades of the ecoinvent database could possibly include such new producing countries.

Finally, the blending of oxygenates such as ethanol and ETBE with gasoline may in the longer term (and sometimes already does) have direct implications on the formulation (i.e. quality) of gasoline used for blending purposes. With the generalization of such oxygenates, indeed, refiners are likely to adapt the formulation and quality of the gasoline fractions used for blending purposes. In order to establish a more accurate life-cycle inventory of ethanol and ETBE fuel blends, the fossil component should ideally be adapted, according to the actual practise of refiners. This would mean implementing the life-cycle inventory of blendstocks for oxygenate blending (BOB), according to the specifications of the final fuel blend.

Abbreviations

% vol.	percentage volume
% wt.	percentage weight
BOB	blendstock of oxygenate blending
BR	Brazil
CA	Canada
CED	Cumulative Energy Demand
CH	Switzerland
CHF	Swiss Franc
CI (engine)	compression ignition (engine)
CN	China
CO_2	carbon dioxide
DDGS	distiller’s dried grains with solubles

E5	mixture of 5% (vol.) biodiesel with 95% (vol.) conventional gasoline
E10	mixture of 10% (vol.) biodiesel with 90% (vol.) conventional gasoline
E85	mixture of 85% (vol.) biodiesel with 15% (vol.) conventional gasoline
EPFL	Swiss Federal Institute of Technology of Lausanne
ETBE	ethyl tert-butyl ether
EtOH	ethanol
EU	European Union
FFV	flexible fuel vehicle
FR	France
GE	Canton of Geneva
GHG	greenhouse gas
H_2O	water
H_3PO_4	phosphoric acid
HCl	hydrochloric acid
HHV	higher heating value
IC (engine)	internal combustion (engine)
IFP	Institut Français du Pétrole
IPCC	Intergovernmental Panel for Climate Change
K	potassium (element)
kg	kilogram
kWh	kilowatt-hour
l	litres
LASEN	Laboratory of Energy Systems (EPFL)
LCI	life cycle inventory
LCIA	life cycle inventory assessment
LHV	lower heating value
MJ	megajoules, 10^6 joules
Ml	million litres
MO-process	multi-output process
MON	Motor Octane Number
Mt	million tons
MTBE	methyl tert-butyl ether
N	nitrogen (element)
Na_3PO_4	sodium phosphate
NaOH	sodium hydroxide
NREL	National Renewable Energy Laboratory (US)
P	phosphorous (element)
RER	Europe (region)
RON	Research Octane Number

RVP	Reid Vapour Pressure
SHF	separate hydrolysis and fermentation
SSF	simultaneous hydrolysis and fermentation
SSCF	simultaneous hydrolysis and co-fermentation
t	metric tons
TBA	tertiary butyl alcohol
US	United States
US$	United States Dollar
VD	Canton of Vaud

Glossary of terms

Anhydrous ethanol

Anhydrous ethanol refers to ethanol with a maximum water content of 0.3% wt.

Bagasse

Bagasse is the biomass remaining after stalks of sugarcane, sorghum, and alikes are crushed to extract their juice.

Catalyst

In chemistry, a catalyst is a substance that decreases the activation energy of a chemical reaction without itself being changed at the end of the chemical reaction. Catalysts participate in reactions but are neither reactants nor products of the reaction they catalyse.

Cellulase

Cellulase is an enzyme complex which breaks down cellulose to glucose. Three general types of enzymes make up the cellulase enzyme complex. Endocellulase breaks internal bonds to disrupt the crystalline structure of cellulose and expose individual cellulase polysaccharide chains. Exocellulase cleaves 2-4 units from the ends of the exposed chains produced by endocellulase, resulting in the tetrasaccharides or disaccharide such as cellobiose. Cellobiase or beta-glucosidase hydrolyses the endocellulase product into individual monosaccharides.

Cellulose

Cellulose (formula: $(C_6H_{10}O_5)_n$, where "n" denotes the total number of glucose monomer units) is a long-chain polymeric polysaccharide carbohydrate of beta-glucose. It forms the primary structural component of green plants. Lignin and cellulose, considered together, are termed lignocellulose, which (as wood) is the most common biopolymer on Earth.

DDGS

DDGS (distiller’s dried grains with solubles) is the product obtained after the removal of ethanol by distillation from the yeast fermentation of a grain or grain mixture by condensing and drying at least ¾ of the solids by the methods employed in the grain distilling industry.

Dehydration

In chemistry, dehydration refers to a type of elimination reaction that involves the loss of water (H_2O) from a molecule. In the specific field of ethanol production, dehydration refers to the final stage of anhydrous ethanol production, the object of which is to lower the water content of ethanol from 95% wt. to 99.7% wt.

Distillation

Distillation is a method of separation of substances based on differences in their volatilities. In the specific field of ethanol production, distillation refers to the separation of ethanol and water.

Enzyme

Enzymes are proteins that accelerate, or catalyze, chemical reactions.

Ethoxylation

Ethoxylation is a chemical process in which ethylene oxide is added to fatty acids in order to make them more soluble in water.

Fermentation

Ethanol fermentation (performed by yeast and some types of bacteria) is the chemical reaction which involves the breaking of simple sugars down to ethanol and carbon dioxide.

Furfural

Furfural (synonyms: furan-2-carboxaldehyde, fural, furfuraldehyde, pyromucic aldehyde; CAS No. 98-01-1) is an aromatic aldehyde, with a ring structure. Its chemical formula is $C_5H_4O_2$. In its pure state, it is a colorless oily liquid with the odor of almonds, but upon exposure to air it quickly becomes yellow. The chemical compound furfural is an industrial chemical derived from a variety of agricultural by-products, and sawdust.

Fusel alcohols (or fusel oils)

Fusel alcohols, also sometimes referred to as 'fusel oils', are higher order (more than two carbon atoms) alcohols formed by fermentation and present in cider, mead, beer, wine, and spirits to varying degrees. The term fusel is the German for "bad liquor".

Glucose

Glucose is an aldohexose, a monosaccharide containing six carbon atoms and including an aldehyde functional group. It has chemical formula $C_6H_{12}O_6$. Glucose is one of the most important carbohydrates in biology. It is used by cells as a source of energy and as a metabolic intermediate.

Gypsum

Gypsum is a very soft mineral composed of calcium sulfate dihydrate, with the chemical formula $CaSO_4 \cdot 2H_2O$.

Hemicellulose

A hemicellulose can be any of several heteropolymers (matrix polysaccharides) present in almost all cell walls along with cellulose. Their molecular weights are usually lower than that of cellulose and they have a weak undifferentiated structure compared to crystalline cellulose. The chains bind with pectin to cellulose to form a network of cross-linked fibres. Hemicelluloses include xylan, glucuronoxylan, arabinoxylan, glucomannan, and xyloglucan.

Hydrated ethanol

Hydrated ethanol often refers to ethanol with a purity of 95-96%, i.e. a water content of the order of 4-5% wt.

Hydrolysis

Hydrolysis is a chemical reaction or process in which a molecule is split into two parts by reacting with a molecule of water (H_2O). One of the parts gets an OH^- from the water molecule and the other part gets an H^+ from the water.

Hydrolyzate

The hydrolyzate is the product of the hydrolysis reaction (see hydrolysis).

Ion (resp cation, anion)

An ion is an atom, group of atoms, or subatomic particle with a net electric charge. A negatively charged ion, which has more electrons in its electron shells than it has protons in its nuclei, is known as an anion. A positively-charged ion, which has fewer electrons than protons, is known as a cation.

Isobutene

Isobutene (synonyms: isobutylene, methyl-propene) is one of the four isomers of alkenes with the chemical formula C_4H_8. All four of these hydrocarbons have four carbon atoms and one double bond in their molecules, but have different chemical structures.

Kiln

A kiln is a thermally insulated chamber or oven in which a controlled temperature regime is produced.

Lignin

Lignin is a chemical compound that is most commonly derived from wood and is an integral part of the cell walls of plants. It is the second most abundant organic compound on earth after cellulose. Lignin makes up about one-quarter to one-third of the dry mass of wood.

Lignocellulosic biomass

Lignocellulosic biomass refers to biomass composed primarily by lignin and cellulose. Examples of lignocellulosic biomass are all types of trees, grasses and agricultural residues such as stover, bagasse, straw, etc.

Molasses

Molasses is a thick syrup by-product from the processing of the sugarcane or sugar beet into sugar. The word molasses comes from the Greek word *mellas* (honey). The quality of molasses depends on the maturity of the sugar cane or beet, the amount of sugar extracted, and the method of extraction.

Molecular sieve

A molecular sieve is a material containing tiny pores of a precise and uniform size that is used as an adsorbent for gases and liquids. Molecules small enough to pass through are adsorbed while larger molecules are not. It is different from a common filter in that it operates on a molecular level. For instance, a water molecule may be small enough to pass through while larger molecules are not. Because of this, they often function as a desiccant. Molecular sieve can absorb water up to 22% of its own weight.

Octane number

The octane number (also referred to as octane index or octane index) is a measure of the autoignition resistance of gasoline and other fuels used in spark-ignition internal combustion engines.

Oxygenate

The term ‘oxygenate’ usually refers to oxygenated fuels. Oxygenates are usually added to increase the octane number of the fuel and improve its combustion, thereby reducing carbon monoxide and hydrocarbons created during the combustion of the fuel.

Photochemical smog

Smog is a kind of air pollution. the name is a combination of the two words smoke and fog. While classic smog results from large amounts of coal burning in an area and is caused by a mixture of smoke and sulphur dioxide, photochemical smog (first described in the 1950s) results from the chemical reaction of sunlight, nitrogen oxides (NO_x) and volatile organic compounds (VOC's) in the atmosphere, leaving airborne particles (called particulate matter) and ground-level ozone.

Saccharification

Synonym of hydrolysis (see hydrolysis).

Splash blending

Splash blending efers to the blending of fuels performed at the filling station directly.

Starch

Starch is a complex carbohydrate insoluble in water. It is used by plants as a way to store excess glucose. Biochemically, starch is a combination of two polymeric carbohydrates (polysaccharides) called amylose and amylopectin, both polymers of glucose. A typical starch polymer chain consists of around 2500 glucose molecules in their varied forms of polymerisation. In general, starches have the formula $(C_6H_{10}O_5)_n$, where "n" denotes the total number of glucose monomer units.

Stillage

Stillage (see also vinasses) refers to the liquid waste stream resulting from the distillation process in the ethanol industry.

Vinasses

Vinasses (see also stillage) refers to the liquid waste stream resulting from the distillation process in the ethanol industry.

Vapour pressure

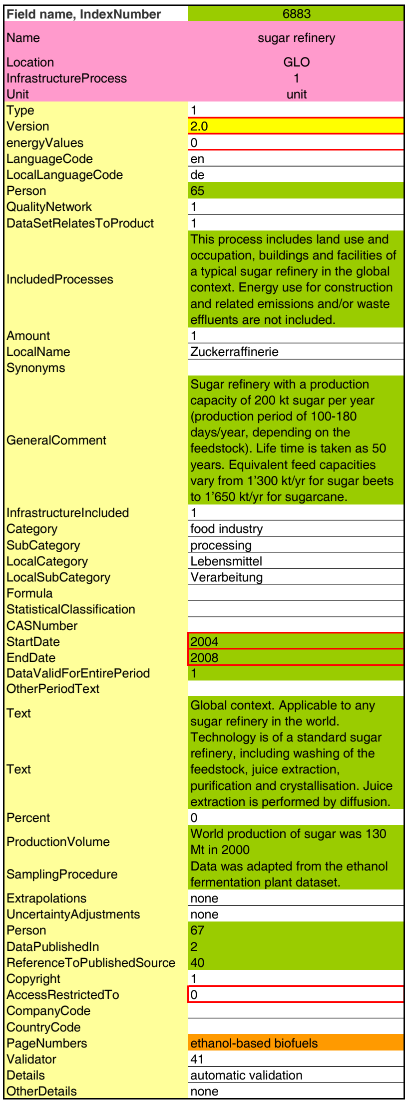
Vapour pressure is the pressure of a vapour in equilibrium with its non-vapour phases. Most often the term is used to describe a liquid's tendency to evaporate (i.e. the tendency of molecules and atoms to escape from a liquid or a solid). A substance with a high vapour pressure at normal temperatures is often referred to as volatile. The higher the vapour pressure of a material at a given temperature, the lower the boiling point.

Xylose

Xylose is an aldopentose, a monosaccharide containing five carbon atoms and including an aldehyde functional group. It has chemical formula $C_5H_{10}O_5$. Xylose is found in the embryos of most edible plants.

Appendices: EcoSpold Meta Information

Tab. A. 22 EcoSpold Meta Information of 'sugar refinery', GLO



Field name, IndexNumber	6883
Name	sugar refinery
Location	GLO
InfrastructureProcess	1
Unit	unit
Type	1
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This process includes land use and occupation, buildings and facilities of a typical sugar refinery in the global context. Energy use for construction and related emissions and/or waste effluents are not included.
Amount	1
LocalName	Zuckerraffinerie
Synonyms	
GeneralComment	Sugar refinery with a production capacity of 200 kt sugar per year (production period of 100-180 days/year, depending on the feedstock). Life time is taken as 50 years. Equivalent feed capacities vary from 1'300 kt/yr for sugar beets to 1'650 kt/yr for sugarcane.
InfrastructureIncluded	1
Category	food industry
SubCategory	processing
LocalCategory	Lebensmittel
LocalSubCategory	Verarbeitung
Formula	
StatisticalClassification	
CASNumber	
StartDate	2004
EndDate	2008
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Global context. Applicable to any sugar refinery in the world.
Text	Technology is of a standard sugar refinery, including washing of the feedstock, juice extraction, purification and crystallisation. Juice extraction is performed by diffusion.
Percent	0
ProductionVolume	World production of sugar was 130 Mt in 2000
SamplingProcedure	Data was adapted from the ethanol fermentation plant dataset.
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 23 EcoSpold Meta Information of 'sugar beet, in sugar refinery', CH

Field name, IndexNumber	6327
Name	sugar beet, in sugar refinery
Location	CH
InfrastructureProcess	0
Unit	kg
Type	5
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This dataset includes the transport of sugar beets to the sugar refinery, and the processing of sugar beets to sugar, molasses (72% dry matter) and pulps (25.6% dry matter). System boundary is at the sugar refinery. Treatment of waste effluents is included. Packaging of the sugar is not included.
Amount	1
LocalName	Zuckerrüben, in Zuckerherstellung
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg sugar, respectively 1 kg of molasses (72% dry matter) and 1 kg of pulps (25.6% dry matter). The multioutput-process 'sugar beet, in sugar refinery' delivers the co-products 'sugar, from sugar beet, at sugar refinery' and 'molasses, from sugar beet, at sugar refinery' and 'pulps, from sugar beet, at sugar refinery. Economic allocation with allocation factor for common stages of 91.7% to sugar, 4.5% to molasses and 3.8% to pulps. Allocation is done according to carbon balance for CO2 emissions.
InfrastructureIncluded	1
Category	food industry
SubCategory	processing
LocalCategory	Lebensmittel
LocalSubCategory	Verarbeitung
Formula	
StatisticalClassification	
CASNumber	
StartDate	1998
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	Data from 1998 to 2005, typical technology for the production of sugar from sugar beet
Text	Data is from sugar producer in CH, industrial data
Text	Sweet juice is extracted from the sugar beets by diffusion. The juice is then purified and crystallized to sugar. Molasses come as a by-product of the crystallization process.
Percent	0
ProductionVolume	Production of sugar was 250 kt in Switzerland in 2004
SamplingProcedure	Data is from sugar producer in CH, industrial data
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 24 EcoSpold Meta Information of ‘molasses, in distillery’, CH

Field name, IndexNumber	6843
Name	molasses, from sugar beet, in distillery
Location	CH
InfrastructureProcess	0
Unit	kg
Type	5
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This dataset includes the transport of molasses to the distillery, and the processing of molasses to hydrated ethanol (95%) and molasses stillage syrup (58% dry matter). System boundary is at the distillery. Dehydration to anhydrous ethanol is not included.
Amount	1
LocalName	Melasse, aus Zuckerrüben, in Ethanolvergärungsanlage
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol 95% wet basis), respectively 1 kg of stillage syrup (wet basis) from molasses. The multioutput-process 'sugar beet molasses, in distillery' delivers the co-products 'ethanol, 95% in H2O, from sugar beet molasses, at distillery' and 'syrup, from sugar beet molasses, at distillery'. Economic allocation with allocation factor for common stages of 94.5% to ethanol. Allocation is done according to carbon balance for CO2 emissions.
InfrastructureIncluded	1
Category	biomass
SubCategory	fuels
LocalCategory	Biomasse
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	1998
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	Data from 1998 to 2005, current technology for the production of ethanol from sugar-based feedstocks
Text	Data is from the etha+ project (Alcosuisse, CH)
Text	The process is similar to that of sugarbeet-to-ethanol. The production of syrup from stillage includes pre-concentration and concentration. The syrup is 58% dry matter and is used as animal feed.
Percent	0
ProductionVolume	Production volume of ethanol for use as a fuel was 1-1.5 Ml in 2005 in CH
SamplingProcedure	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 25 EcoSpold Meta Information of ‘potatoes, in distillery’, CH

Field name, IndexNumber	6839
Name	potatoes, in distillery
Location	CH
InfrastructureProcess	0
Unit	kg
Type	5
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This dataset includes the transport of potatoes to the distillery, and the processing of potatoes to hydrated ethanol (95%) and DDGS (distiller's dried grains with solubles, 90% dry matter). System boundary is at the distillery. Dehydration to anhydrous ethanol is not included.
Amount	1
LocalName	Kartoffeln, in Ethanolvergärungsanlage
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol 95% wet basis), respectively 1 kg of DDGS (wet basis) from potatoes. The multioutput-process 'potatoes, in distillery' delivers the co-products 'ethanol, 95% in H2O, from potatoes, at distillery' and 'DDGS, from potatoes, at distillery'. Economic allocation with allocation factor for common stages of 95.6% to ethanol. Allocation is done according to carbon balance for CO2 emissions.
InfrastructureIncluded	1
Category	biomass
SubCategory	fuels
LocalCategory	Biomasse
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	2002
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	Data from 2002 to 2005, current technology for the production of ethanol from starch-based feedstocks, applied to potatoes
Text	Data is from the etha+ project (Alcosuisse, CH)
Text	The process is similar to that of wheat-to-ethanol or yet dry-milling corn-to-ethanol. The production of DDGS from stillage includes separation of draff, concentration, drying and granulation. DDGS are used as animal feed.
Percent	0
ProductionVolume	Production volume of ethanol for use as a fuel was 1-1.5 Ml in 2005 in CH
SamplingProcedure	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 26 EcoSpold Meta Information of ‘wood, in distillery’, CH

Field name, IndexNumber	6841
Name	wood, in distillery
Location	CH
InfrastructureProcess	0
Unit	kg
Type	5
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This dataset includes the transport of wood from the forest to the distillery, and the processing of wood (u=80%) to hydrated ethanol (95%) and electricity. System boundary is at the distillery. Dehydration to anhydrous ethanol is not included. Process heat and power supply is ensured by the combustion of unconverted solids.
Amount	1
LocalName	Holz, in Ethanolvergärungsanlage
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol 95% wet basis), respectively 1 kWh of electricity from wood (u=80%, i.e. 55% dry matter). The multioutput-process 'wood, in distillery' delivers the co-products 'ethanol, 95% in H2O, from wood, at distillery' and 'electricity, from wood, at distillery'. Economic allocation with allocation factor for common stages of 99.7% to ethanol. Allocation is done according to carbon balance for CO2 emissions.
InfrastructureIncluded	1
Category	biomass
SubCategory	fuels
LocalCategory	Biomasse
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	1999
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	Data from 1999 to 2006, pilot scale, near-future technology
Text	Data is adapted to Swiss conditions from NREL ethanol process design from yellow poplar (1999)
Text	Ethanol is produced by dilute acid pre-hydrolysis and simultaneous saccharification and co-fermentation (SSCF) of lignocellulosic biomass. Process heat and power supply is ensured by the combustion of unconverted solids. Excess electricity is exported to the power grid.
Percent	0
ProductionVolume	Production volume of ethanol for use as a fuel was 1-1.5 Ml in 2005 in CH
SamplingProcedure	Data is adapted to Swiss conditions from NREL ethanol process design from yellow poplar, modelling by ENERS (CH)
Extrapolations	Direct emissions (resulting from the combustion of unconverted solids, incl. lignin) are based on the the combustion of wood chips (with emission control), according to the corresponding dry matter content, carbon content and energy content.
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 27 EcoSpold Meta Information of datasets relating to rye-to-ethanol, RER

Field name, IndexNumber	6825	6892
Name	rye, in distillery	ethanol, 99.7% in H2O, from biomass, at distillation
Location	RER	RER
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This dataset includes the transport of rye grains to the distillery, and the processing of rye grains to hydrated ethanol (95%) and DDGS (92% dry matter). System boundary is at the distillery. Dehydration to anhydrous ethanol is not included.	This dataset includes the dehydration of hydrated ethanol (95%) to anhydrous ethanol (99.7%). Hydrated ethanol input is rye-based ethanol, prduced in the RER context. Treatment of waste streams is included.
Amount	1	1
LocalName	Roggen, in Ethanolvergärungsanlage	Ethanol, 99.7% in H2O, aus Biomasse, ab Destillation
Synonyms		Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol
GeneralComment	Inventory refers to the production of 1 kg hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol wet basis), respectively 1 kg of DDGS (wet basis) from rye grains. The multioutput-process 'rye, in distillery' delivers the co-products 'ethanol, 95% in H2O, from rye, at distillery' and 'DDGS, from rye, at distillery'. Economic allocation with allocation factor for common stages of 97.7% to ethanol. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg anhydrous ethanol 99.7% (dry basis, i.e. 1.003 kg anhydrous ethanol wet basis). Dehydration is carried out by molecular sieve technology. Ethanol is produced from rye, in the average RER context.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		C2H6O
StatisticalClassification		
CASNumber		000064-17-5
StartDate	2002	2002
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 2002 to 2006, current technology for the production of ethanol from starch-based feedstocks	Data from 2002 to 2006, current technology for the production of ethanol from starch-based feedstocks
Text	Data is from the etha+ project (Alcosuisse, CH), adapted to RER context	Data is from the etha+ project (Alcosuisse, CH), adapted to RER context
Text	The process is similar to that of wheat-to-ethanol or yet dry-milling corn-to-ethanol. The production of DDGS from stillage includes separation of draff, concentration, drying and granulation. DDGS are used as animal feed.	Dehydration is done by molecular sieve technology.
Percent	0	0
ProductionVolume	Production volume of ethanol for use as a fuel was 620 Ml in 2004 in RER	Production volume of ethanol for use as a fuel was 620 Ml in 2004 in RER
SamplingProcedure	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 28 EcoSpold Meta Information of ‘sugarcane, in sugar refinery’, BR

Field name, IndexNumber	6852
Name	sugarcane, in sugar refinery
Location	BR
InfrastructureProcess	0
Unit	kg
Type	5
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This dataset includes the transport of sugarcane to the sugar refinery and the processing of sugarcane to sugar, ethanol (95% w/w), bagasse (79% dry matter, excess), excess electricity and vinasse from ethanol production. System boundary is at the sugar refinery. Treatment of waste effluents is not included (most wastewater is spread over the fields nearby). Packaging is not included.
Amount	1
LocalName	Zuckerrohr, in Zuckerherstellung
Synonyms	
GeneralComment	Inventory refers to the production of 1 kg sugar, respectively 1 kg of ethanol (95% w/w dry basis, i.e. 1.05 kg hydrated ethanol 95% wet basis), 1 kg of excess bagasse (wet basis, 79% dry matter), 1 kWh of electricity and 1 kg of vinasse. The multioutput-process 'sugarcane, in sugar refinery' delivers the co-products 'sugar, from sugarcane, at sugar refinery' and 'ethanol, 95% in H2O, from sugarcane molasses, at sugar refinery', 'bagasse, from sugarcane, at sugar refinery', 'electricity, bagasse, sugarcane, at sugar refinery' and 'vinasse, from sugarcane molasses, at sugar refinery'. Economic allocation with allocation factor for common sugar production stages of 80-85% to sugar, 10-11% to ethanol. Allocation according to carbon balance for CO2.
InfrastructureIncluded	1
Category	food industry
SubCategory	processing
LocalCategory	Lebensmittel
LocalSubCategory	Verarbeitung
Formula	
StatisticalClassification	
CASNumber	
StartDate	1994
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	Data from 1994 to 2006, current technology for the production of ethanol from sugarcane
Text	Data is from various sugar and ethanol producers in Brazil; some data is adapted from sugar producer in CH
Text	Juice extraction is performed through milling (not diffusion). The juice is then purified and crystallized to sugar according to standard processes. Ethanol is produced by standard fermentation and distillation techniques. Energy supply is done by combustion of the bagasse resulting from the extraction stage. The two main products are sugar and ethanol.
Percent	0
ProductionVolume	Production of sugar was 26.6 Mt in Brazil in 2004-2005
SamplingProcedure	Data is from various sugar and ethanol producers in Brazil (incl. literature data) and from sugar producer in CH
Extrapolations	Direct emissions (resulting from the combustion of sugarcane bagasse) are based on the the combustion of wood chips (without emission control), according to the corresponding dry matter content, carbon content and energy content.
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	ethanol-based biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 29 EcoSpold Meta Information of datasets relating to corn-to-ethanol, US

Field name, IndexNumber	6822	6891
Name	corn, in distillery	ethanol, 99.7% in H2O, from biomass, at distillation
Location	US	US
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This dataset includes the transport of corn grains to the distillery, and the processing of corn grains to hydrated ethanol (95%) and DDGS (92% dry matter). System boundary is at the distillery. Dehydration to anhydrous ethanol is not included. The process described corresponds to the dry-milling technology.	This dataset includes the dehydration of hydrated ethanol (95%) to anhydrous ethanol (99.7%). Hydrated ethanol input is corn-based ethanol, produced in the US context. Treatment of waste streams is included.
Amount	1	1
LocalName	Mais, in Ethanolvergärungsanlage	Ethanol, 99.7% in H2O, aus Biomasse, ab Destillation
Synonyms		Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol
GeneralComment	Inventory refers to the production of 1 kg hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol wet basis), respectively 1 kg of DDGS (wet basis) from corn grains. The multioutput-process 'corn, in distillery' delivers the co-products 'ethanol, 95% in H2O, from corn, at distillery' and 'DDGS, from corn, at distillery' (dry-milling technology). Economic allocation with allocation factor for common stages of 97.6% to ethanol. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg anhydrous ethanol 99.7% (dry basis, i.e. 1.003 kg anhydrous ethanol wet basis). Dehydration is carried out by molecular sieve technology. Ethanol is produced from corn, in the average US context.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		C2H6O
StatisticalClassification		
CASNumber		000064-17-5
StartDate	1990	1990
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1990 to 2006, current dry-mill technology for the production of ethanol from corn	Data from 1990 to 2006, current dry-mill technology for the production of ethanol from corn
Text	Data is from the etha+ project (Alcosuisse, CH), adapted to US context	Data is from the etha+ project (Alcosuisse, CH), adapted to US context
Text	The process described corresponds to the dry-milling corn-to-ethanol technology. The production of DDGS from stillage includes separation of draff, concentration, drying and granulation. DDGS are used as animal feed.	Dehydration is done by molecular sieve technology.
Percent	0	0
ProductionVolume	Production volume of ethanol for use as a fuel was 12'000 Ml in 2004 in US	Production volume of ethanol for use as a fuel was 12'000 Ml in 2004 in US
SamplingProcedure	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)	Data is from the etha+ project (Alcosuisse, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 30 EcoSpold Meta Information of datasets relating to sorghum-to-ethanol, CN

Field name, IndexNumber	6827	6893
Name	sweet sorghum, in distillery	ethanol, 99.7% in H2O, from biomass, at distillation
Location	CN	CN
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This dataset includes the transport of sorghum to the distillery and the processing of sorghum to ethanol (95% w/w), bagasse (70% dry matter, excess), excess electricity and vinasse from ethanol production. System boundary is at the ethanol distillery. Treatment of waste effluents is not included (most wastewater is spread over the fields nearby).	This dataset includes the dehydration of hydrated ethanol (95%) to anhydrous ethanol (99.7%). Hydrated ethanol input is sorghum-based ethanol, produced in the CN context. Treatment of waste streams is included.
Amount	1	1
LocalName	Zuckerhirse, in Ethanolvergärungsanlage	Ethanol, 99.7% in H2O, aus Biomasse, ab Destillation
Synonyms		Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol
GeneralComment	Inventory refers to the production of 1 kg of hydrated ethanol 95% (dry basis, i.e. 1.05 kg hydrated ethanol 95% wet basis), respectively 1 kg of excess bagasse (70% dry matter), 1 kWh of electricity and 1 kg of vinasse. The multioutput-process 'sweet sorghum, in ethanol distillery' delivers the co-products 'ethanol, 95% in H2O, from sweet sorghum, at distillery', 'bagasse, from sweet sorghum, at distillery', 'electricity, bagasse, sorghum, at distillery' and 'vinasse, from sweet sorghum, at distillery'. Economic allocation with allocation factor for common stages of 91% to ethanol. Allocation according to carbon balance for CO2.	Inventory refers to the production of 1 kg anhydrous ethanol 99.7% (dry basis, i.e. 1.003 kg anhydrous ethanol 99.7% wet basis). Dehydration is carried out by molecular sieve technology. Ethanol is produced from sweet sorghum, in the average CN context.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		C2H6O
StatisticalClassification		
CASNumber		000064-17-5
StartDate	1992	1992
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1992 to 2005, current technology	Data from 1992 to 2005, current technology
Text	Data is from the etha+ project (Alcosuisse, CH) and the ASIATIC project (LASEN, CH), adapted to CN context	Data is from the etha+ project (Alcosuisse, CH) and the ASIATIC project (LASEN, CH), adapted to CN context
Text	Juice extraction is performed through milling (not diffusion). The juice is then converted to ethanol by standard fermentation and distillation techniques. Energy supply is done by combustion of the bagasse resulting from the extraction stage. The main product is ethanol.	Dehydration is done by molecular sieve technology.
Percent	0	0
ProductionVolume	Production volume of ethanol for use as a fuel was 1'500 Ml in 2004 in CN	Production volume of ethanol for use as a fuel was 1'500 Ml in 2004 in CN
SamplingProcedure	Data is from the etha+ project (Alcosuisse, CH) and the ASIATIC project (LASEN, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)	Data is from the etha+ project (Alcosuisse, CH) and the ASIATIC project (LASEN, CH), technology by French ethanol plant supplier, modelling by ENERS (CH)
Extrapolations	Direct emissions (resulting from the combustion of sorghum bagasse) are based on the the combustion of wood chips (without emission control), according to the corresponding dry matter content, carbon content and energy content.	Direct emissions (resulting from the combustion of sorghum bagasse) are based on the the combustion of wood chips (without emission control), according to the corresponding dry matter content, carbon content and energy content.
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 31 EcoSpold Meta Information of datasets relating to ETBE

Field name, IndexNumber	6384	32013	33069
Name	ethyl tert-butyl ether, from bioethanol, at plant	petrol, 15% vol. ETBE additive, with ethanol from biomass, at refinery	petrol, 4% vol. ETBE additive, with ethanol from biomass, at refinery
Location	RER	RER	RER
InfrastructureProcess	0	0	0
Unit	kg	kg	kg
Type	1	1	1
Version	2.0	2.0	2.0
energyValues	0	0	0
LanguageCode	en	en	en
LocalLanguageCode	de	de	de
Person	65	65	65
QualityNetwork	1	1	1
DataSetRelatesToProduct	1	1	1
IncludedProcesses	This process includes the production of ethyl tert-butyl ether (ETBE), at the oil refinery. ETBE is the result of the reaction between 45.1% wt. anhydrous ethanol from biomass and 54.9% wt. isobutene (side-product of oil refineries).	This process includes the production unleaded gasoline blended with 15% vol. ethyl tert-butyl ether (ETBE), at the oil refinery. Operation of storage tanks and refinery facilities are taken into account. All processes on the refinery site specifically related to the production of ETBE are included.	This process includes the production unleaded gasoline blended with 4% vol. ethyl tert-butyl ether (ETBE), at the oil refinery. Operation of storage tanks and refinery facilities are taken into account. All processes on the refinery site specifically related to the production of ETBE are included.
Amount	1	1	1
LocalName	Ethyl Tert-butyl Ether, aus Bioethanol, ab Werk	Benzin, 15% Vol. ETBE Zusatz, mit Ethanol aus Biomasse, ab Raffinerie	Benzin, 4% Vol. ETBE Zusatz, mit Ethanol aus Biomasse, ab Raffinerie
Synonyms	2-ethoxy-2-methylpropane//2-methyl-2-ethoxypropane//ETBE//ethyl tert-butyl ether//ethyl tertiary butyl ether//ethyl tertio butyl ether//ethyl tert-butyl oxide//tert-butyl ethyl ether	2-ethoxy-2-methylpropane//2-methyl-2-ethoxypropane//ETBE//ethyl tert-butyl ether//ethyl tertiary butyl ether//ethyl tertio butyl ether//ethyl tert-butyl oxide//tert-butyl ethyl ether//alkohol//alcohol dehydrated//algrain//anhydrol//cologne spirit//cologne spirits (alcohol)//denatured alcohol//ethyl alcohol//ethanol//ethanol 200 proof//ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol	2-ethoxy-2-methylpropane//2-methyl-2-ethoxypropane//ETBE//ethyl tert-butyl ether//ethyl tertiary butyl ether//ethyl tertio butyl ether//ethyl tert-butyl oxide//tert-butyl ethyl ether//alkohol//alcohol dehydrated//algrain//anhydrol//cologne spirit//cologne spirits (alcohol)//denatured alcohol//ethyl alcohol//ethanol//ethanol 200 proof//ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol
GeneralComment	Inventory refers to the production of 1 kg ETBE, at the oil refinery. ETBE can be incorporated at up to 15% vol. in gasoline, as an oxygenate, according to the current (2005) European Norms. Anhydrous bioethanol is produced from rye, in the RER context. Naphtha is used as a proxy dataset for isobutene. This process is applied in France and Spain and possibly in Germany. Fossil and biogenic carbon contents are respectively 45.4% and 25.4%, according to the respective shares of isobutene (53% wt.) and ethanol (47% wt.).	Inventory refers to the blending of 15% vol. ETBE to low-sulphur gasoline, on the oil refinery site. Fossil and biogenic carbon contents are respectively 80.3% and 3.7%.	Inventory refers to the blending of 4% vol. ETBE to low-sulphur gasoline, on the oil refinery site. Fossil and biogenic carbon contents are respectively 84.9% and 1.0%.
InfrastructureIncluded	1	1	1
Category	biomass	oil	oil
SubCategory	fuels	fuels	fuels
LocalCategory	Biomasse	Erdöl	Erdöl
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	C6H14O		
StatisticalClassification			
CASNumber	000637-92-3	000637-92-3	000637-92-3
StartDate	1998	2004	2004
EndDate	2006	2008	2008
DataValidForEntirePeriod	1	1	1
OtherPeriodText	Data from 1998 to 2002, current technology		
Text	Mainly based on EU studies. ETBE is largely produced in France, Spain and possibly soon in Germany.	Mainly based on EU studies. ETBE is largely produced in France, Spain and possibly soon in Germany.	Mainly based on EU studies. ETBE is largely produced in France, Spain and possibly soon in Germany.
Text	Production of ETBE according to the IFP technology	Simple blending of the two components of the fuel blend	Simple blending of the two components of the fuel blend
Percent	0	0	0
ProductionVolume	Production volume of ETBE in RER was about 900 Ml, in 2004.	Production volume of ETBE in RER was about 900 Ml, in 2004.	Production volume of ETBE in RER was about 900 Ml, in 2004.
SamplingProcedure			
Extrapolations	none	none	none
UncertaintyAdjustments	none	none	none
Person	67	67	67
DataPublishedIn	2	2	2
ReferenceToPublishedSource	40	40	40
Copyright	1	1	1
AccessRestrictedTo	0	0	0
CompanyCode			
CountryCode			
PageNumbers	ethanol-based biofuels	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41	41
Details	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none

Tab. A. 32 EcoSpold Meta Information of datasets relating to ethanol (99.7% wt.) distribution

Field name, IndexNumber	6888	6889	6890
Name	ethanol, 99.7% in H2O, from biomass, production US, at service station	ethanol, 99.7% in H2O, from biomass, production RER, at service station	ethanol, 99.7% in H2O, from biomass, production CN, at service station
Location	CH	CH	CH
InfrastructureProcess	0	0	0
Unit	kg	kg	kg
Type	1	1	1
Version	2.0	2.0	2.0
energyValues	0	0	0
LanguageCode	en	en	en
LocalLanguageCode	de	de	de
Person	65	65	65
QualityNetwork	1	1	1
DataSetRelatesToProduct	1	1	1
IncludedProcesses	This dataset includes the transport of (corn-based) anhydrous ethanol from distilleries in US to Switzerland (1700 km by rail, 100 km by truck, 7000 km by tanker, 840 km by barge), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of (rye-based) anhydrous ethanol from distilleries in RER to Switzerland (600 km by rail, 150 km by truck), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of (sorghum-based) anhydrous ethanol from distilleries in CN to Switzerland (1350 km by rail, 150 km by truck, 23000 km by tanker), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.
Amount	1	1	1
LocalName	Ethanol, 99.7% in H2O, aus Biomasse, Produktion US, ab Tankstelle	Ethanol, 99.7% in H2O, aus Biomasse, Produktion RER, ab Tankstelle	Ethanol, 99.7% in H2O, aus Biomasse, Produktion CN, ab Tankstelle
Synonyms	Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol	Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol	Alkohol// alcohol dehydrated// algrain// Anhydrol// cologne spirit// cologne spirits (alcohol)// Denatured alcohol// Ethyl alcohol// Ethanol// ethanol 200 proof// Ethanol absolute// ethyl hydrate// ethyl hydroxide// fermentation alcohol// grain alcohol// bioethanol// bio-ethanol
GeneralComment	Inventory refers to the distribution of 1 kg of anhydrous ethanol 99.7% in Switzerland. Ethanol is imported from US and produced from corn grains. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of anhydrous ethanol 99.7% in Switzerland. Ethanol is imported from RER and produced from rye. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of anhydrous ethanol 99.7% in Switzerland. Ethanol is imported from CN and produced from sweet sorghum juice. Distribution to the final consumer (service station) including all necessary transports.
InfrastructureIncluded	1	1	1
Category	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	C2H6O	C2H6O	C2H6O
StatisticalClassification			
CASNumber	000064-17-5	000064-17-5	000064-17-5
StartDate	2004	2004	2004
EndDate	2008	2008	2008
DataValidForEntirePeriod	1	1	1
OtherPeriodText			
Text	Transport through US to East Coast harbour (1700 km by rail and 100 km by road), and then oversea to Rotterdam harbour (7000 km by tanker). Delivery from Rotterdam to Basel (840 km by barge), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Delivery to Geneva or Basel (650 km by rail and 150 km by road), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Transport from Jilin (CN) to the gulf of Bohai (850 km by rail and 150 km by road), and then oversea to Marseille (F) harbour through Suez canal (23000 km by tanker). Delivery from Marseille to Geneva (500 km by train), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.
Text	Distribution of fuels	Distribution of fuels	Distribution of fuels
Percent	0	0	0
ProductionVolume	Production volume of ethanol for use as a fuel was 12'000 Ml in 2004 in US	Production volume of ethanol for use as a fuel was 630 Ml in 2004 in RER	Production capacity of ethanol for use as a fuel was 1'500 Ml in 2005 in CN
SamplingProcedure	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.
Extrapolations	none	none	none
UncertaintyAdjustments	none	none	none
Person	67	67	67
DataPublishedIn	2	2	2
ReferenceToPublishedSource	40	40	40
Copyright	1	1	1
AccessRestrictedTo	0	0	0
CompanyCode			
CountryCode			
PageNumbers	ethanol-based biofuels	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41	41
Details	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none

Tab. A. 33 EcoSpold Meta Information of datasets relating to the distribution of ethanol-based fuel blends

Field name, IndexNumber	6848	6849	32014	33068
Name	petrol, 5% vol. ethanol, from biomass, at service station	petrol, 85% vol. ethanol, from biomass, at service station	petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station
Location	CH	CH	CH	CH
InfrastructureProcess	0	0	0	0
Unit	kg	kg	kg	kg
Type	1	1	1	1
Version	2.0	2.0	2.0	2.0
energyValues	0	0	0	0
LanguageCode	en	en	en	en
LocalLanguageCode	de	de	de	de
Person	65	65	65	65
QualityNetwork	1	1	1	1
DataSetRelatesToProduct	1	1	1	1
IncludedProcesses	This process includes the distribution of E5 (95% vol. low-sulphur gasoline and 5% vol. anhydrous ethanol from biomass) to the end user at the filling station. Operation of storage tanks and petrol stations are taken into account. Emissions from evaporation and treatment of effluents are also included. Excluding emissions from car-washing at petrol stations. Mixing is supposed to be performed directly at the filling station (splash blending).	This process includes the distribution of E85 (15% vol. low-sulphur gasoline and 85% vol. anhydrous ethanol from biomass) to the end user at the filling station. Operation of storage tanks and petrol stations are taken into account. Emissions from evaporation and treatment of effluents are also included. Excluding emissions from car-washing at petrol stations. Mixing is supposed to be performed directly at the filling station (splash blending).	This process includes the distribution of unleaded gasoline blended with 15% vol. ethyl tert-butyl ether (ETBE) to the the end user in CH, at the filling station. The fuel blend is imported from RER, mostly France, by train (165 km). Operation of storage tanks and petrol stations are taken into account. Emissions from evaporation and treatment of effluents are also included. Excluding emissions from car-washing at petrol stations.	This process includes the distribution of unleaded gasoline blended with 4% vol. ethyl tert-butyl ether (ETBE) to the the end user in CH, at the filling station. The fuel blend is imported from RER, mostly France, by train (165 km). Operation of storage tanks and petrol stations are taken into account. Emissions from evaporation and treatment of effluents are also included. Excluding emissions from car-washing at petrol stations.
Amount	1	1	1	1
LocalName	Benzin, 5% Vol. Zusatz Ethanol, 99.7% in H2O, aus Biomasse, ab Tankstelle	Benzin, 85% Vol. Zusatz Ethanol, 99.7% in H2O, aus Biomasse, ab Tankstelle	Benzin, 15% Vol. ETBE Zusatz, Ethanol aus Biomasse, Prod. RER, ab Tankstelle	Benzin, 4% Vol. ETBE Zusatz, Ethanol aus Biomasse, Prod. RER, ab Tankstelle
Synonyms	Alkohol//alcohol dehydrated//algrain//Anhydrol//cologne spirit//cologne spirits (alcohol)//Denatured alcohol//Ethyl alcohol//Ethanol//ethanol 200 proof//Ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol//E5	Alkohol//alcohol dehydrated//algrain//Anhydrol//cologne spirit//cologne spirits (alcohol)//Denatured alcohol//Ethyl alcohol//Ethanol//ethanol 200 proof//Ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol//E85	2-ethoxy-2-methylpropane//2-methyl-2-ethoxypropane//ETBE//ethyl tert-butyl ether//ethyl tertiary butyl ether//ethyl tertio butyl ether//ethyl tert-butyl oxide//tert-butyl ethyl ether//alkohol//alcohol dehydrated//algrain//anhydrol//cologne spirit//cologne spirits (alcohol)//denatured alcohol//ethyl alcohol//ethanol//ethanol 200 proof//ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol	2-ethoxy-2-methylpropane//2-methyl-2-ethoxypropane//ETBE//ethyl tert-butyl ether//ethyl tertiary butyl ether//ethyl tertio butyl ether//ethyl tert-butyl oxide//tert-butyl ethyl ether//alkohol//alcohol dehydrated//algrain//anhydrol//cologne spirit//cologne spirits (alcohol)//denatured alcohol//ethyl alcohol//ethanol//ethanol 200 proof//ethanol absolute//ethyl hydrate//ethyl hydroxide//fermentation alcohol//grain alcohol//bioethanol//bio-ethanol
GeneralComment	Inventory refers to the distribution of 1 kg of E5 (95% vol. low-sulphur gasoline blended with 5% vol. anhydrous ethanol from biomass). Ethanol is partly produced in CH (according to the production mix), and partly imported from RER and BR. Distribution to the final consumer (service station) including all necessary transports. Fossil and biogenic carbon contents are respectively 82.0% and 2.7%.	Inventory refers to the distribution of 1 kg of E85 (15% vol. low-sulphur gasoline blended with 85% vol. anhydrous ethanol from biomass). Ethanol is partly produced in CH (according to the production mix), and partly imported from RER and BR. Distribution to the final consumer (service station) including all necessary transports. Fossil and biogenic carbon contents are respectively 12.4% and 44.7%.	Inventory refers to the distribution of 1 kg unleaded gasoline blended with 15% vol. ethyl tert-butyl ether (ETBE) to the end user, in Switzerland. The fuel blend is imported from the European Union. Distribution to the final consumer (service station) including all necessary transports. Fossil and biogenic carbon contents are respectively 80.3% and 3.7%.	Inventory refers to the distribution of 1 kg unleaded gasoline blended with 4% vol. ethyl tert-butyl ether (ETBE) to the end user, in Switzerland. The fuel blend is imported from the European Union. Distribution to the final consumer (service station) including all necessary transports. Fossil and biogenic carbon contents are respectively 84.9% and 1.0%.
InfrastructureIncluded	1	1	1	1
Category	oil	biomass	oil	oil
SubCategory	fuels	fuels	fuels	fuels
LocalCategory	Erdöl	Biomasse	Erdöl	Erdöl
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	C2H6O	C2H6O		
StatisticalClassification				
CASNumber	000064-17-5	000064-17-5	000637-92-3	000637-92-3
StartDate	2004	2004	2004	2004
EndDate	2008	2008	2008	2008
DataValidForEntirePeriod	1	1	1	1
OtherPeriodText				
Text	The ethanol component is partly produced in Switzerland (25%) and partly imported from the EU (37.5%) and from Brazil (37.5%). The gasoline component corresponds to low-sulphur gasoline used in Switzerland.	The ethanol component is partly produced in Switzerland (25%) and partly imported from the EU (37.5%) and from Brazil (37.5%). The gasoline component corresponds to low-sulphur gasoline used in Switzerland.	Mainly based on EU studies. ETBE is largely produced in France, Spain and possibly soon in Germany. The blend is here mainly imported from Feysin (F) to Geneva (165 km by train), then distributed in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Mainly based on EU studies. ETBE is largely produced in France, Spain and possibly soon in Germany. The blend is here mainly imported from Feysin (F) to Geneva (165 km by train), then distributed in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.
Text	Distribution of fuels	Distribution of fuels	Distribution of fuels	Distribution of fuels
Percent	0	0	0	0
ProductionVolume	Ethanol for use as a fuel as a fuel was limited to 1-1.5 Ml/yr in CH, in 2005.	Ethanol for use as a fuel as a fuel was limited to 1-1.5 Ml/yr in CH, in 2005.	Production volume of ETBE in RER was about 900 Ml, in 2004.	Production volume of ETBE in RER was about 900 Ml, in 2004.
SamplingProcedure	Environmental reports and literature.	Environmental reports and literature.		
Extrapolations	none	none	none	none
UncertaintyAdjustments	none	none	none	none
Person	67	67	67	67
DataPublishedIn	2	2	2	2
ReferenceToPublishedSource	40	40	40	40
Copyright	1	1	1	1
AccessRestrictedTo	0	0	0	0
CompanyCode				
CountryCode				
PageNumbers	ethanol-based biofuels	ethanol-based biofuels	ethanol-based biofuels	ethanol-based biofuels
Validator	41	41	41	41
Details	automatic validation	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none	none

References

ADEME 1996	ADEME (1996). Ecobilan de l'ETBE de betterave. Prepared by Ecobilan for ADEME, CGB and SNPAA, France, 1996.
ADEME 2002	ADEME/DIREM & Ecobilan/PriceWaterhouseCoopers (2002). Bilans énergétiques et gaz à effet de serre des filières de production de biocarburants. Rapport technique, rédigé par Ecobilan/PWC pour l'Agence de l'Environnement et la Maîtrise de l'Energie (ADEME) et la Direction des Ressources Energétiques et Minérales (DIREM), novembre 2002.
Aden et al. 2002	Aden A., et al. (2002). Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis, corn stover. Biotechnology Center for Fuels and Chemicals, National Renewable Energy Laboratory (NREL). NREL Report TP-510-32438, 2002.
ARKENOL 1999	ARKENOL Inc. (1999). Our technology: Concentrated acid hydrolysis. Arkenol website, http://www.arkenol.com/Arkenol%20Inc/tech01.html, retrieved on 3rd May 2006. Copyright 1999 Arkenol.
Avram & Stark 2004	Avram P. & Stark T. (2006). Integration of ethanol production with a sugar factory producing maximum cogeneration. In: International Sugar Journal, Vol. 106, No. 1263, pp. 126-137.
Barros & Perkins 2005	Barros S. & Perkins M. (2005). Brazil sugar, Semi annual 2005. USDA Foreign Agricultural Service.
Beauvais et al. 2004	Beauvais G. et al. (2000). Procédés de production d'éthanol. Projet de design, Département de Génie Chimique, Université de Sherbrooke, 2000.
Berg 2004	Berg C. (2004). World fuel ethanol outlook and analysis. Editor: F.O. Licht, Tunbridge Wells, England, UK.
Borreroa et al. 2003	Borreroa M.A.V., et al. (2003). An environmental management method for sugar cane alcohol production in Brazil. Biomass and Bioenergy, 25, 287-299.
Bullard et al. 2004	Bullard M., et al. (2003). The impacts of creating a domestic UK bioethanol industry. Prepared by ADAS Consulting Ltd. & ECOFYS UK Ltd., for the East of England Development Agency, Report EEDA-02/77.
Cheesman 2004	Cheesman O. D. (2004). Environmental Impacts of Sugar Production. Wallingford, CABI Publishing.
Chiaramonti et al. 2002	Chiaramonti D., Agterberg A., Grassi G., Grimm H.P. & Coda B. (2002). Large bio-ethanol project from sweet sorghum in china and italy (echit): Description of site, process schemes and main products. In: 12th European Conference on Biomass for Energy, Industry and Climate Protection, 17-21 June 2002, Amsterdam, The Netherlands.
Coltrain 2004	Coltrain D. (2004). Economic issues with ethanol. Department of Agricultural Economics, Kansas Cooperative Development Center, Kansas State University, Manhattan, KS.
Copersucar 2006	Sugar and Alcohol. Institutional, the Sugar and Alcohol Academy. On 03.06. Copersucar Internet website, 2006.
Cundiff et al. 1993	Cundiff J.S., et al. (1993). Juice expression from sweet sorghum. Biological Systems Engineering, Unpublished annual report. Blacksburg, VA, USA.
Dale & Tyner 2005	Dale R. & Tyner W. (2005). Economic analysis of dry-milling technologies. Purdue University, DOE Grant # DE-FG36-04G014220.

Dias de Oliveira et al. 2005	Dias de Oliveira M., Vaughan B., and Rykiel E. (2005). Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. In BioScience, American Institute of Biological Sciences (AIBS), Vol. 55, No. 7, pp. 593-602 (10).
Durante & Miltenberger 2004	Durante D. & Miltenberger M. (2004). Net energy balance of ethanol production. Ethanol Across America education campagin. Produced in collaboration of the U.S Department of Agriculture.
Edwards et al. 2006	Edwards R., Larivé J.-F., Mahieu V. & Rouveirolles P. (2006). Well-to-wheels analysis of future automotive fuels and powertrains in the European context. version 2b, May 2006, EUCAR, CONCAWE & JRC of the European Commission.
El Bassam 1998	El Bassam N. (1998). Energy plant species: Their use and impact on environment and development. James & James (Science Publishers) Ltd, London.
Elsayed et al. 2003	Elsayed M.A. et al. (2003). Carbon and energy balances for a range of biofuels options. Prepared for the Department of Trade & Industry. Sheffield Hallam University, UK.
ENERS 2005	ENERS (2005). Projet etha+: Business plan. Rédigé par ENERS Energy Concept, en collaboration avec CBEF SA (Cabinet Béguin d'expertise fiscale), pour Alcosuisse.
ENERS 2006a	ENERS (2006). Bilan énergétique de filières de production de bioéthanol dans le contexte helvétique selon une approche d'analyse de cycle de vie. Rédigé par ENERS Energy Concept pour Alcosuisse, Mars 2006.
ENERS 2006b	ENERS (2006). Bilan énergétique de filières de production de bioéthanol dans le contexte brésilien selon une approche d'analyse de cycle de vie. Rédigé par ENERS Energy Concept pour Alcosuisse, Avril 2006.
Enguidanos et al. 2002	Enguidanos M., Soria A., Kavalov B. & Jensen P. (2002). Techno-economic analysis of bio-alcohol production in the EU: a short summary for decision-makers. Institute for Prospective Technological Studies (IPTS), European Commission Joint Research Centre (JRT), Report EUR 20280 EN, May 2002.
ETEK 2006	ETEK/EtanolTeknik AB (2006). ETEK website, http://www.etek.se/main.cfm, Pilot plant, retrieved on 3rd May 2006. Copyright 2006 ETEK.
European Commission 2005	European Commission (2005). Aide d'état n° N334/2005, Taux d'accise réduit en faveur des biocarburants. C(2005)5960, Bruxelles, 23.12.2005.
FAPRI 2005	FAPRI-UMC (2006). Implications of increased ethanol production for US agriculture. Prepared by the Food and Agricultural Policy Research Institute, College of Agriculture, Food and Natural Resources, University of Missouri, Report #10-05, August 22, 2005.
Farrell et al. 2006	Farrell A.E. et al. (2006). Ehanol can contribute to energy and environmental goals. In: Science, Vol. 311, pp.506-508, 27 January 2006.
Ferguson 2003	Ferguson A. (2003). Implication of the USDA 2002 'Update on Ethanol from Corn'. In the Optimum Population Trust, Vol. 3, No. 1, Manchester, UK.
Frischknecht et al. 2002	Frischknecht R. & Jungbluth N. (2002) Qualitätsrichtlinien ecoinvent 2000. Arbeitspapier v5.4, Schweizer Zentrum für Ökoinventare, Dübendorf, CH.
Frischknecht et al. 2004a	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2004a) Overview and Methodology. Final report ecoinvent 2000 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Frischknecht et al. 2004b	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hischier R., Hellweg S., Nemecek T., Rebitzer G. and Spielmann M. (2004b) Code of Practi-

	ce. Final report ecoinvent 2000 No. 2. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Frischknecht et al. 2004c	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004c) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Gnansounou et al. 2005	Gnansounou E. Dauriat A. & Wyman C.E. (2005). Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. In: Bioresource Technology 96 (2005) pp. 985-1002.
Gnansounou & Dauriat 2005	Gnansounou E., Dauriat A. (2005). Ethanol fuel from biomass: A review. In Journal of Scientific & Industrial Research (JSIR), Vol. 64, November 2005, pp. 809-821.
Goldemberg 2000	Goldemberg J. (2000). O Futuro energético desejado para o Brasil. Universidade de Campinas.
Graboski et al. 2002	Graboski M. & McClelland J. (2002). A rebuttal to 'Ethanol Fuels: Energy, Economics and Environmental Impacts by David Pimentel'. In International Sugar Journal, 104: (1240). 162-163.
Graboski 2002	Graboski M. (2002). Fossil energy use in the manufacture of corn ethanol. Prepared for the National Corn Growers AssociationColorado School of Mines, Golden, CO.
Graf & Koehler 2000	Graf A. & Koehler T. (2000). Oregon cellulose ethanol study, An evaluation of the potential for ethanol production in Oregon using cellulose-based feedstocks. Prepared by Bryan & Bryan Inc. and Celilo Group, for submission to the Oregon Office of Energy, June 2000.
Hamelinck et al. 2003	Hamelinck C., van Hooijdonk G. & Faaij A. (2003). Prospects for ethanol from lignocellulosic biomass : Techno-economic performance as development progresses. Report NWS-E-2003-55, ISBN 90-393-2583-4. Science Technology Society, Copernicus Institute, University of Utrecht, NL.
Hammerschlag 2006	Hammerschlag R. (2006). Ethanol's energy return on investment: A survey of the literature 1990-present. In: Environmental Science & Technology, 40(6) pp. 1744-1750, 2006.
Ho 1989	Ho S.P. (1989). Global warming impact of ethanol versus gasoline. Presented at the 1989 National Conference “Clean air issues and America’s motor fuel business”, Washington DC.
IEA 2004	IEA (2004). Biofuels for transport. An international perspective. Prepared by the International Energy Agency (IEA), Paris, April 2004.
INTERIS 2002	INTERIS (2002). Etude budgétaire pour une unité de production d’alcool carburant à partir de céréales, mélasses de betteraves et pommes de terre. Rapport 2270C-DE-02, rédigé par Maguin Interis, pour Alcosuisse.
IOGEN 2006	IOGEN (2006). Cellulose ethanol / What is cellulose ethanol? / Pocess, IOGEN website, http://www.iogen.ca/cellulose_ethanol/what_is_ethanol/process.html, retrieved on 3rd May 2006. Copyright 2006 IOGEN.
Janssens 1992	Janssens M., Meekers E., Chapelle J. & Jacquemin J.C. (1992). Production de bio-éthanol à partir de sorgho sucrier et de la betterave sucrière en Wallonie : Etude de faisabilité. Sorghum Organisation and Research Group for High Altitude or Latitude (SORGHAL), décembre 1992.

Jungbluth 2004	Jungbluth N. (2004) Erdöl. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Keeney & DeLuca 1992	Keeney D.R. & DeLuca T.H. (1992). Biomass as an energy source for the midwestern US. In Amer. J. Alternative Agric., Vol. 7, pp. 137-143.
Kim & Dale 2002	Kim S. & Dale B.E. (2002). Allocation procedure in ethanol production system from corn grain. In: International Journal of LCA, OnlineFirst, May 2002.
Kim & Dale 2005	Kim S. & Dale B.E. (2005). Cumulative energy and global warming impact of biomass for biobased products. In Journal of Industrial Ecology, Vol. 7, No. 3-4, pp. 146-162.
Knauf et al. 2004	Knauf M. & Moniruzzaman M. (2004). Lignocellulosic biomass processing: A perspective. In: International Sugar Journal, Vol. 106, No. 1263, 147-150.
Koizumi 2003	Koizumi T. (2003). The Brazilian ethanol programme: impacts on world ethanol and sugar markets. Commodity Policy and Projections Service, Commodities and Trade Division, Food and Agriculture Office (FAO), 24 June 2003.
Krummenacher 2006	Krummenacher P. (2006). Compte rendu: Alcosuisse etha+2004, Visite MBE Werk, Zörbig, plus personal communication of M. P. Krummenacher, BG Ingénieurs Conseil, Lausanne, 2006.
LASEN 2000	Fromentin A., Biollay F., Dauriat A. & Lucas-Porta H. (2000). Caractérisation de filières de production de bioéthanol dans le contexte helvétique. Prepared by the Laboratory of Energy Systems (LASEN) of EPFL for the Swiss Federal Office of Energy. Energy research programme, Biomass, 2000.
LASEN 2002	Sarlos G., Gnansounou E. & Dauriat A. (2002). Etude comparative de carburants par analyse de leur cycle de vie. Prepared by the Laboratory of Energy Systems (LASEN) of EPFL for Alcosuisse. Report 415.105, 2002.
LASEN 2004a	Gnansounou E. & Dauriat A. / LASEN (2004). Production of bioethanol in the Chinese context: The cases of Liaoning and Guangxi. In ASIATIC Project (Agriculture and small to medium scale industries in peri-urban areas through ethanol production for transport in china), 5th EU Framework programme.
LASEN 2004b	Gnansounou E. & Dauriat A. (2004). Etude comparative de carburants par analyse de leur cycle de vie. Prepared by the Laboratory of Energy Systems (LASEN) of EPFL for Alcosuisse. Report 420.100, 2004.
LBST 2002	L-B-Systemtechnik (2002). Well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems: A European study. Prepared for GM, with the participation of BP, ExxonMobil, Shell and TotalFinaElf, September 2002.
Levelton 1999	Levelton engineering (1999). Assessment of net emissions of greenhouse gases from ethanol-gasoline blends in Southern Ontario. Prepared by Levelton Engineering Ltd. and (S&T)2 Consulting Inc., J.E. & Associates for Agriculture and Agri-Food Canada.
Li 1997	Li D. (1997). Sweet sorghum: A multipurpose crop with great potential for exploitation next century. Proceedings of the First International Sweet Sorghum Conference. Li D. (Eds.), Institute of Botany, Chinese Academy of Sciences, China.
Li et al. 2001	Li J., Zhuang X., DeLaquil P. & Larson E.D. (2001). Biomass energy in China and its potential. In: Energy for Sustainable Development, Vol.5, No.4, 2001.

Liu & Li 1999	Liu R. & Li Y. (1999). Practical technologies of integrated energy. Science and Technology Press, Shenyang, Liaoning, China.
Lorenz & Morris 1995	Lorenz D. & Morris D. (1995). How much energy does it take to make a gallon of ethanol? Updated and revised. Institute for Local Self-Reliance, Washington DC.
Lynd et al. 1996	Lynd L.R., Elander R.T. & Wyman C.E. (1996). Likely features and costs of mature biomass ethanol technology. In: Applied Biochemistry and Biotechnology 57/58, 741-761.
Lynd & Wang 2004	Lynd L.R. & Wang M.Q. (2004). A product-nonspecific framework for evaluating the potential of biomass-based products to displace fossil fuels. In: Journal of Industrial Ecology 7(3-4), pp.117-146.
Macedo 2004	Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. NIPE/UNICAMP in collaboration with Copersucar, for the Secretariat of the Environment, Government State of São Paulo, 2004.
Marland & Turhollow 1990	Marland G. & Turhollow A.F. (1990). CO2 emissions from the production and combustion of fuel ethanol from corn. Prepared by the Oak Ridge National Laboratory, Oak Ridge, Tennessee. Environmental Sciences Division, No. 3301. US Department of Energy.
McAloon et al. 2000	McAloon A., et al. (2000). Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. A joint study sponsored by the US Department of Agriculture and the US Department of Energy. National Renewable Energy Laboratory, Contract No. DE-AC36-99-GO10337, October 2000.
Mehlin 2003	Mehlin M., et al. (2003). Renewable fuels for cross-border transportation. Prepared ba the German Aerospace Centre (Institute of Transport Research), Institue for Energy and Environment and the University of Stuttgart /Institute for Road and Transportation Science), for the European Commission, Directorate General for Environment, June 2003.
Möllersten et al. 2003	Möllersten K., et al. (2003). Potential market niche for biomass energy with CO2 capture and storage: Opportunities for energy supply with negative CO2 emissions. Biomass and Bioenergy, 25(3), 273-285.
Morris & Ahmed 1992	Morris D. & Ahmed I. (1992). How much energy does it take to make a gallon of ethanol? Institute for Self Reliance, Washington DC.
NOVEM 2003	NOVEM (2003). Ligno cellulosic-ethanol, A second opinion. Report 2GAVE-03.11. Authors: van Zessen E., Weismann M., Bakker R.R., Elbersen H.W., Reith J.H. & den Uil H. Commissioned by the Netherlands Agency for Energy and Environment (NOVEM) in the frame of the GAVE programme.
O'Connor (2003)	O'Connor D. (2003). Wheat and barley as ethanol feedstocks. (S&T)2 Consultants Inc. World Summit on Ethanol for Transportation, Quebec City, November 2003.
Patyk et al. 2000	Patyk A., Reinhardt A. & Jungk N.C. (2000). Bioenergy for Europe : Which ones fit best? A comparative analysis for the Community. Research funded by The European Commission in the framework of the FAIR V Programme, contract CT 98 3832, November 2000.
Patzek 2003	Patzek T. (2003). Ethanol from corn: clean renewable fuel for the future, or drain on our resources and pockets? In: Natural Resources Research.
Patzek 2004	Patzek T. (2004). Thermodynamics of the corn-ethanol biofuel cycle. In: Critical Reviews in Plant Sciences, Vol. 23, No. 6, pp. 519-567.

Pimentel 1991	Pimentel D. (1991). Ethanol fuels: energy security, economics, and the environment. In: Jour. Agri. Environ. Ethics, Vol. 4, pp. 1-13.
Pimentel 1996	Pimentel D. & Pimentel M. (1996). Food, energy and society. Colorado University Press, CO, Revised Edition, 363 p.
Pimentel 1998	Pimentel D. (1998). Energy and dollar costs of ethanol production with corn. In: M. King Hubbert Center for Petroleum Supply Studies, Newsletter 98/2, Colorado School of Mines, Golden, US.
Pimentel 2002	Pimentel D. (2002). Limits of biomass utilization. In: Encyclopedia of Physical Science and Technology, 3rd Edition, Vol. 2, pp. 159-171, New-York Academic Press.
Pimentel et al. 2002	Pimentel D., et al. (2002). Renewable energy: Current and potential issues. In: BioScience, 52: (12), pp.1111-1120.
Pimentel 2003	Pimentel D. (2003). Ethanol fuels: energy balance, economics, and environmental impacts are negative. In: Natural Resources Research, Vol. 12, No. 2, pp. 127-134.
Pimentel & Patzek 2005	Pimentel D. & Patzek T. (2005). Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. In: Natural Resources Research, Vol. 14, No. 1, pp. 65-76.
Poitrat et al. 1998	Poitrat E., et al. (1998). Total costs and benefits of biomass in selected regions of the European Region (BioCosts). INRA/ADEME, Contract Ref. JOR3-CT95-0006. Research funded by the European Commission in the framework of the Non Nuclear Energy Programme, JOULE III, May 1998.
PRA 2003	PRA (2003). Ethanol et autres produits dérivés des sucres. Prepared by Prairie Research Associates (PRA) Inc. for Agriculture and Agri-food Canada, 23 July 2003.
Punter et al. (2004)	Punter G., Rickeard D., Larivé J.F., Edwards R., Mortimer N., Horne R., Bauen A. & Woods J. (2004). Well-to-wheel evaluation for production of ethanol from wheat. A report by the LowCVP (Low Carbon Vehicle Partnership) Fuels Working Group, WTW Sub-group, FWG-P-04-024.
Rabotovao 2005	Rabotovao P.M. (2005). Projet de développement de la filière « canne et sucre » à Madagascar. Université Libre Entreprise de Madagascar (ULEM), septembre 2005.
Rains 1993	Rains G.C., Cundiff J.S. & Welbaum G.E. (1993). Sweet sorghumn for a Piedmont ethanol industry. In: J. Janick and J.E. Simon (eds.), New crops, pp. 394-399. Wiley, New York.
Raveendran 2004	Raveendran T.S. (2004). Sweet sorghum. Centre for plant breeding and genetics, Tamil Nadu Agricultural University, India.
Reith et al. 2002	Reith J.H. et al. (2004). Co-production of bioethanol, electricity and heat from biomass residues. In: 12^{th} European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, June 17-22, 2002, Amsterdam, The Netherlands.
Reynolds 2002	Reynolds R.E. (2002). Infrastructure requirements for an expanded fuel ethanol industry. Phase II project deliverable report, Ethanol project. Prepared by Downstream Alternatives Inc. for the Oak Ridge National Laboratory (ORNL) Subcontract No. 4500010570.
Rossell 2005	Rossell C. (2005). O Setor Sucroalcooleiro e a Produção de Etanol. Transformações após o Protocolo de Kioto. Projeto Etanol, NIPE/UNICAMP, Grupo Energia, 2005.

Schleser 1994	Schleser R. (1994). Ethanol production in Hawaii. Processes, feedstocks, and current economic feasibility of fuel grade ethanol production in Hawaii. Prepared for State of Hawaii, Department of Business, Economic Development & Tourism, final report, July 1994.
Shapouri et al. 1995	Shapouri H., Duffield J.A. & Graboski M.S. (1995). Estimating the net energy balance of corn ethanol. In US Department of Agriculture (USDA), Economic Research Service, Agricultural Economic Report No. 721.
Shapouri et al. 2002	Shapouri H., Duffield J.A. & Wang M. (2002). The energy balance of corn ethanol: an update. In USDA, Office of Energy Policy and New Uses, Agricultural Economics Report No. 813, 14 p.
Shapouri et al. 2004	Shapouri H., Duffield J.A., McAloon A. & Wang M. (2004). The 2001 net energy balance of corn-ethanol (preliminary). U.S. Department of Agriculture (USDA), Washington, DC.
Sheehan et al. 2004	Sheehan J., Aden A., Paustian K., Killian K., Brenner J., Walsh M. & R. Nelson (2004). Energy and environmental aspects of using corn stover for fuel ethanol. In: Journal of Industrial Ecology 7(3-4), pp.117-146.
SORGHAL 2003	SORGHAL (2003). Bioethanol from sweet sorghum flow chart. In ASIATIC Project (Agriculture and small to medium scale industries in peri-urban areas through ethanol production for transport in china), 5th EU Framework programme.
Spindler et al. 1991	Spindler D.D., Wyman C.E. & Grohmann K. (1991). The simultaneous saccharification and fermentation of pretreated woody crops to ethanol. In: Applied Biochemistry and Biotechnology 28/29, 773-786.
Steiner & Tuchschmidt 2006	Steiner S. & Tuchschmidt M. (2006) Production of sugar from sugarcane and ethanol production from sugarcane molasses in Brazil. Prepared for the Swiss Federal Office of the Environment (FOEN), the Swiss Federal Office of Energy (FOE) and the Swiss Federal OFfice of Agriculture (FOAG).
Tiffany & Eidman 2003	Tiffany D.G. & Eidman V.R. (2003). Factors associated with success of fuel ethanol producers. Staff paper series P03-7, Department of Applied Economics, College of Agricultural, Food and Environmental Sciences, University of Minnesota, August 2003.
UNICA 2004	UNICA (2004). Brazil's sugar and ethanol. Energy and Environmental Commodities. Saõ Paulo.
van Vaals & Braks 2003	van Vaals M. & Braks P. (2003). Ethanol from biomass: A Dutch case study. Rabobank International. In: Industry Note, Food and Agribusiness Research, Issue 078-2003, February 2003.
VIEWLS 2005	VIEWLS (2005). Shift gear to biofuels, Results and recommendations from the VIEWLS project (Clear Views on Clean Fuels). European Commission (NNE5-2001-00619), November 2005.
Wang et al. 1999	Wang M., Saricks C., & Santini D. (1999). Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. USDOE Argonne National laboratory, Center for Transportation Research, Argonne, IL.
Wooley et al. 1999	Wooley R., et al. (1999). Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis, current and futuristic scenarios. Biotechnology Center for Fuels and Chemicals, National Renewable Energy Laboratory (NREL). NREL Report TP-580-26157, 1999.
Woods 2000	Woods J. (2000). Integrating sweet sorghum and sugarcane for bioenergy: modelling the potential for electricity and ethanol production in SE Zimbabwe. Ph.D

	thesis, Division of Life Sciences, King's College London, University of London, January 2000.
Woods & Bauen 2003	Woods J. & Bauen A. (2003). Technology status review and carbon abatement potential of renewable transport fuels in the UK. Prepared by Imperial College London Centre for Energy Policy and Technology (ICCEPT), for the Department of Trade and Industry / New and Renewable Energy Programme, 2003.
Worley et al. 1992	Worley J.W., Vaughan D.H. & Cundiff J.S. (1991). Energy analysis of ethanol production from sweet sorghum. In: Bioresource Technology, 40(92), 263-273.
Wright 1988	Wright J.D. (1988). Ethanol from biomass by enzymatic hydrolysis. In: Chemical Engineering Progress, 62-74.
Wright et al. 1898	Wright J.D., Wyman C.E. & Grohmann K. (1988). Simultaneous saccharification and fermentation of lignocellulose: Process evaluation. In: Applied Biochemistry and Biotechnology 18, 75-89.
Wyman 1999	Wyman C.E. (1999). Biomass Ethanol: Technical Progress, Opportunities, and Commercial Challenges. In: Annual Review of Energy and the Environment 24, 189-226.
Wyman 2001	Wyman C.E. (2001). 20 years of trials, tribulations, and research progress on bioethanol technology: Selected key events along the way. In: Applied Biochemistry and Biotechnology 91/93, 5-21.
Wyman 2004	Wyman C.E. (2004). Ethanol Fuels. In: Cutler Cleveland (Eds.), Encyclopedia of Energy. Elsevier, New York.
Zah & Hischier 2004	Zah R. and Hischier R. (2004) Life Cycle Inventories of Detergents. Final report ecoinvent 2000 No. 12. EMPA St. Gallen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
ZAF 2002	Zuckerfabriken Aarberg & Frauenfeld (2002). Environmental report 2002, plus personal communication of M. H.-R. Fankhauser, 2002.
ZAF 2005	Zuckerfabriken Aarberg & Frauenfeld (2005). Transformation de betteraves sucrières en 2005. Aarberg, 20 décembre 2005.

17 Oil-based biofuels

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Summary

The present chapter deals with the life cycle inventory of oil-based biofuels and related processes. The expression ‘oil-based biofuels’ here refers to oil-based fuels (for use in the transportation sector) derived from the processing of vegetable oil (i.e. oil from rape, soybeans, palm, sunflower or groundnut, but also from waste cooking oil). Through the process of esterification, the resulting purified oil, often referred to as ‘methyl ester’ or even more commonly ‘biodiesel’, may be used as an alternative to conventional diesel fuel in transports.

Crude purified vegetable oils may also be used for heat production but such an application is not covered in the present study.

17.1 Introduction

Today, transportation relies almost entirely on oil-based fuels and about 30% of the world’s fossil fuel consumption is related to transports. According to the principle of sustainability, it is commonly accepted that a modern society has an obligation to preserve non-renewable energy sources and to look for new applications of renewable energy. The reduction of fossil energy reserves and the associated environmental impact are the two main reasons that lead to consider the use of alternative fuels in the sector of transportation.

Fuels derived from biomass, also referred to as biofuels, are not only potentially renewable, but are also sufficiently similar to fossil fuels (which also began as biomass) to provide direct substitution. It seems also to be a promising alternative to fossil fuels in the short term. Transformation technologies of oil-containing biomass into biofuels have long been proven at an industrial scale, and methyl ester (also commonly referred to as ‘biodiesel’) has been able to compete with conventional gasoline thanks to low production costs and/or specific financial incentives.

Biodiesel is an alternative fuel similar to conventional or ‘fossil’ diesel, which can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. The process used to convert these oils to biodiesel is called ‘transesterification’. In recent years, the production and use of biodiesel has grown significantly, especially in the European Union (EU), South-East Asia, South America and the United States (US). The production process and use of biodiesel is described in more detail in the following sections.

This chapter documents the life cycle inventories for oil-based biofuel systems contained in the ecoinvent database. The processes relating to oil-based biofuels covered in ecoinvent data are summarized in Tab. 16.1 below.

Tab. 17.1 Overview of the 'oil-based biofuels' unit processes covered within the ecoinvent database.

Name	Location	Category	SubCategory	unit
Oil-based biofuels				
oil mill	CH	biomass	fuels	unit
vegetable oil esterification plant	CH	biomass	fuels	unit
vegetable oil, from waste cooking oil, at plant	CH	biomass	fuels	kg
vegetable oil, from waste cooking oil, at plant	FR	biomass	fuels	kg
vegetable oil, from waste cooking oil, in esterification plant	FR	biomass	fuels	kg
vegetable oil methyl ester, at esterification plant	FR	biomass	fuels	kg
glycerine, from vegetable oil, at esterification plant	FR	chemicals	organics	kg
vegetable oil methyl ester, production FR, at service station	CH	biomass	fuels	kg
rape seeds, in oil mill	CH	biomass	fuels	kg
rape meal, at oil mill	CH	biomass	others	kg
rape oil, at oil mill	CH	biomass	fuels	kg
rape oil, at regional storage	CH	biomass	fuels	kg
rape oil, in esterification plant	CH	biomass	fuels	kg
rape methyl ester, at esterification plant	CH	biomass	fuels	kg
glycerine, from rape oil, at esterification plant	CH	chemicals	organics	kg
rape methyl ester, at regional storage	CH	biomass	fuels	kg
palm fruit bunches, in oil mill	MY	biomass	fuels	kg
palm kernel meal, at oil mill	MY	biomass	others	kg
palm kernel oil, at oil mill	MY	chemicals	organics	kg
palm oil, at oil mill	MY	biomass	fuels	kg
palm oil, in esterification plant	MY	biomass	fuels	kg
palm methyl ester, at esterification plant	MY	biomass	fuels	kg
glycerine, from palm oil, at esterification plant	MY	chemicals	organics	kg
palm methyl ester, production MY, at service station	CH	biomass	fuels	kg
rape seeds, in oil mill	RER	biomass	fuels	kg
rape meal, at oil mill	RER	biomass	others	kg
rape oil, at oil mill	RER	biomass	fuels	kg
rape oil, in esterification plant	RER	biomass	fuels	kg
rape methyl ester, at esterification plant	RER	biomass	fuels	kg
glycerine, from rape oil, at esterification plant	RER	chemicals	organics	kg
potassium sulphate, as K2O, from rape oil, at esterification plant	RER	chemicals	inorganics	kg
rape methyl ester, production RER, at service station	CH	biomass	fuels	kg
soybeans, in oil mill	US	biomass	fuels	kg
soybean oil, at oil mill	US	biomass	fuels	kg
soybean meal, at oil mill	US	biomass	others	kg
soybean oil, in esterification plant	US	biomass	fuels	kg
soybean methyl ester, at esterification plant	US	biomass	fuels	kg
glycerine, from soybean oil, at esterification plant	US	chemicals	organics	kg
soybean methyl ester, production US, at service station	CH	biomass	fuels	kg
soybeans, in oil mill	BR	biomass	fuels	kg
soybean oil, at oil mill	BR	biomass	fuels	kg
soybean meal, at oil mill	BR	biomass	others	kg
soybean oil, in esterification plant	BR	biomass	fuels	kg
soybean methyl ester, at esterification plant	BR	biomass	fuels	kg
glycerine, from soybean oil, at esterification plant	BR	chemicals	organics	kg
soybean methyl ester, production US, at service station	CH	biomass	fuels	kg

The documentation is structured as follows:

- Section 17.2 (Raw material resources) provides some general information on the availability of feedstocks for oil-based production in the world and in Switzerland.
- Section 17.3 (Characterisation of energy carrier) presents the most significant chemical and physical properties of biodiesel (or methyl-ester) as a transportation fuel. In the present case, these properties will be compared to those of conventional diesel, with which it competes.
- Section 17.4 (Use and application of energy carrier) describes the fields of application of biodiesel and raw vegetable oil. Although the present report focuses mainly on transportation, the possible use of oil-based biofuels for heat production is also considered briefly.

- Section 17.5 (Description of the processes) describes the various production processes involved in the present chapter (incl. waste oil refining, crude oil extraction and transesterification).
- Sections 17.6 to 17.14 describe the actual datasets considered in the present chapter, including system characterization (definition of the system boundaries, detailed description of the production process, interactions of the various products and by-products and allocation issues of multi-output processes) and life cycle inventory data
- Section 17.15 (Data Quality Considerations) discusses the data quality indicators for the inventory of all the processes included in the present chapter.
- Section 17.16 (Cumulative Results and Interpretation) presents and discusses LCI results and values for the cumulative energy demand of selected processes in this chapter. These results are compared to similar results published in related articles and reports.
- Section 17.17 finally gives the conclusions.

17.2 Resources of biodiesel and related feedstocks

17.2.1 Resources of rape seeds, soybeans and oil palm fruit

The data in Fig. 17.1 presents the production of rape seeds in the world and the three largest producers, for the period 1990-2005. China, Canada and India represent approximately 60% of the world production in 2005. The six following producers (Germany, France, the UK, Poland, Austria and the Czech Republic) are located in the EU and represent altogether about 30% of the world production.

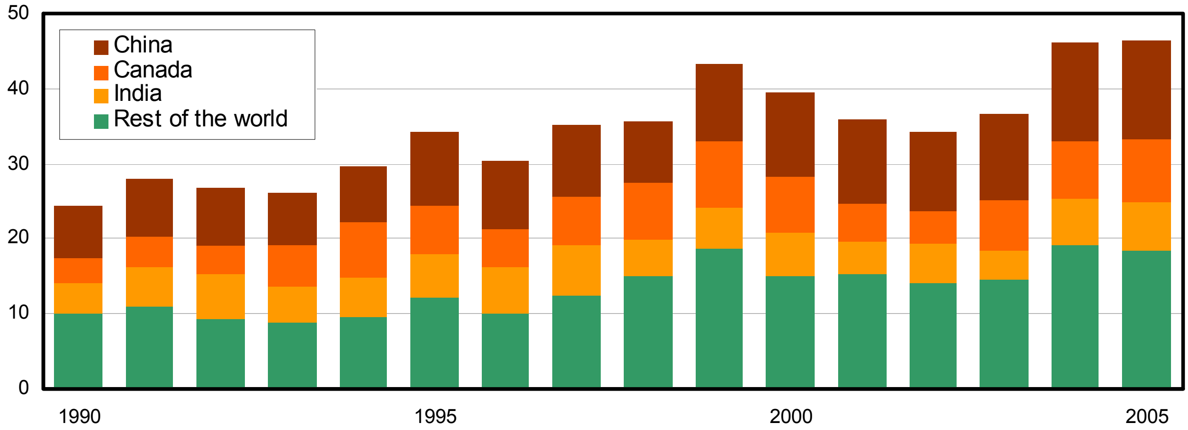

Fig. 17.1 World production of rape seeds (in million tons) for the period 1990-2005 (source: FAO/FAOSTAT 2006).

The data in Fig. 17.2 presents the production of palm fruit in the world and the three largest producers, from 1990 to 2005. Malaysia, Indonesia and Nigeria represent 86% of the world production in 2005.

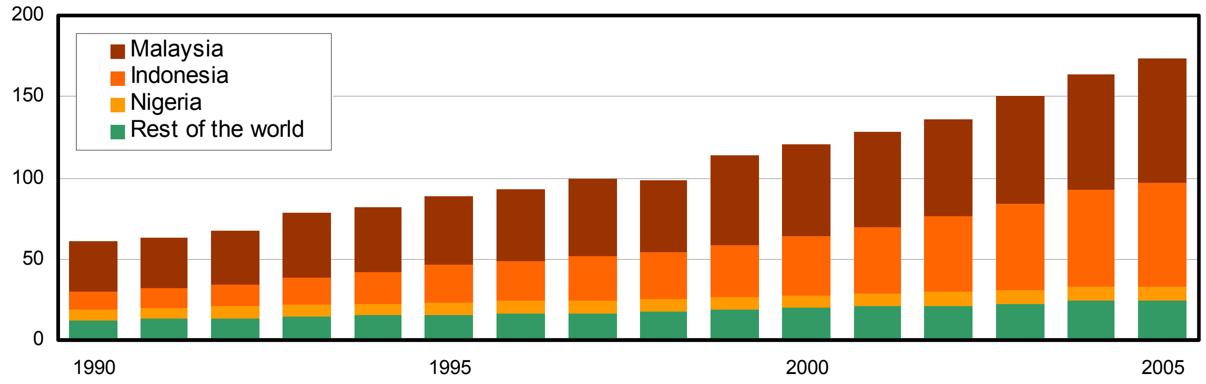

Fig. 17.2 **World production of palm fruits (in million tons) for the period 1990-2005 (source: FAO/FAOSTAT 2006).**

The data in Fig. 17.3 presents the production of soybeans in the world and the three largest producers, for the period 1990-2005. The US, Brazil and Argentina represent about 82% of the world production in 2005.

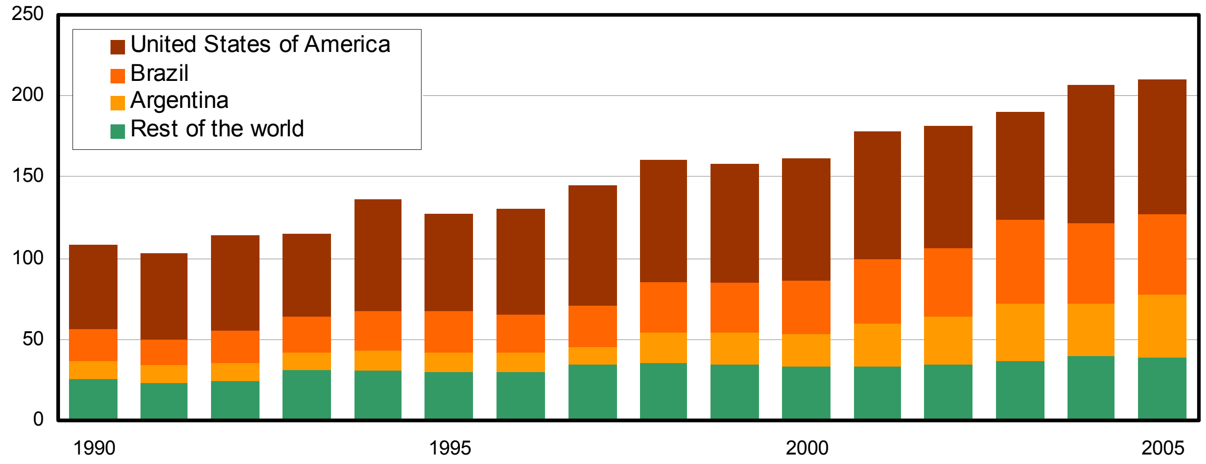

Fig. 17.3 **World production of soybeans (in million tons) for the period 1990-2005 (source: FAO/FAOSTAT 2006).**

Apart from rape seeds in the EU25, where the use for biodiesel production reaches 40% (i.e. 6 Mt/yr out of 15 Mt/yr), the use of oil crops is largely dominated by food and feed uses. However, the market for biofuels does represent significant opportunities for developing countries (in terms of exports) and the distribution between the various uses may well change considerably in future years.

17.2.2 Biodiesel production in the World

The European Union is the leading region of the world in terms of development of a biodiesel sector. In 2005, it counted 10 producer countries with a production above 50’000 t/yr (EBB 2006). Biodiesel production in the EU has progressed from 1’500 kt in 2003 to 1’900 kt in 2004 (+26%) and has known a record boost in 2005 with an increase of 1’300 kt to reach almost 3’200 kt/yr (i.e. + 68%). Given the political framework (EC Directive 2003/30/EC), the production is expected to grow even further in the near future (EBB 2006; UFOP 2006; EurObserv’ER 2005; O’Connor 2004a; Bendz 2005; Partenaires Diester 2005). Biodiesel production data for the period 2000-2005 is shown in Tab. 17.2 and Fig. 17.4.

Tab. 17.2 World biodiesel for the period 2000-2005 (EBB 2006; EurObserv'ER 2005; UFOP 2006; O'Connor 2004a).

Rapeseed production (Mt)	2000	2001	2002	2003	2004	2005
World	688	1'068	1'256	1'574	1'990	3'468
European Union (EU25)	680	1'049	1'207	1'504	1'895	3'184
Germnany	340	450	550	715	1'035	1'669
France	200	351	366	357	348	492
Italy	-	120	210	273	320	396
Austria	-	-	25	32	57	85
Czech Republik	-	62	40	69	47	133
Denmark	-	-	10	40	40	-
Other EU Member States	-	-	6	18	48	409
United States	8	19	49	70	95	284
Brazil	-	-	-	Marginal today, but may play a major role on the international biodiesel maket in the near future.		
Malaysia	-	-	-			
Thailand	-	-	-			
Canada	-	-	-			

The US is today the only country outside the EU to show significant production of biodiesel (284 kt in 2005, i.e. a 200% increase compared to 2004). However, countries like Brazil, Malaysia, Thailand or yet Canada, have an enormous potential for biodiesel production and development in the first three countries has been developing at a very fast pace lately.

In accordance with the data presented in paragraph 17.2.1, biodiesel development in the US and Brazil is based largely upon soybeans (see Fig. 17.3), whereas it is largely related to palm fruit in Malaysia and Thailand (see Fig. 17.2).

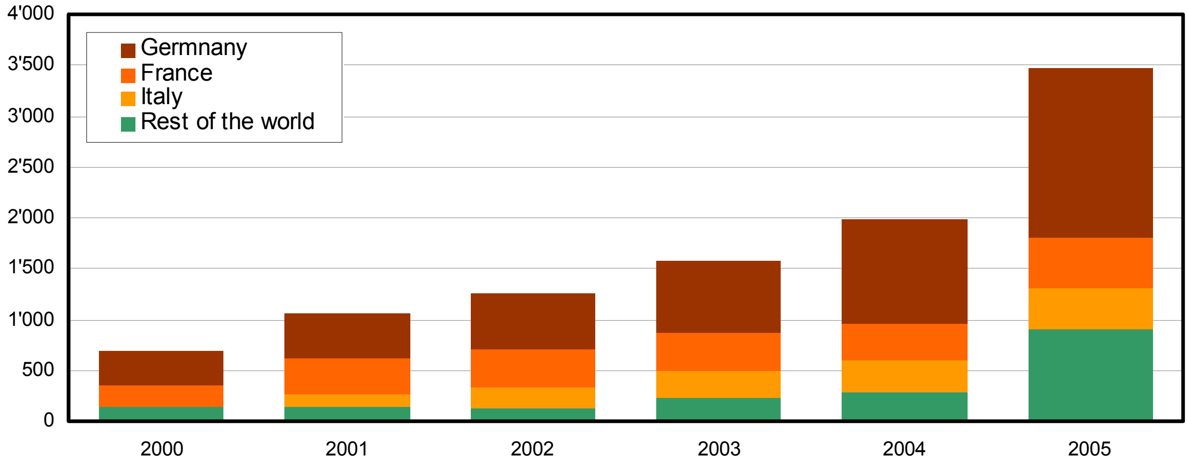

Fig. 17.4 World production of biodiesel (in kt/yr) for the period 1990-2005 (EBB 2006; UFOP 2006; O'Connor 2004a).

17.2.3 Biodiesel production in Switzerland

The main agricultural feedstocks for potential biodiesel production in Switzerland are rape seeds, sunflower seeds, and soybeans. The potential from waste cooking vegetable oil is also being considered.

The production and surface areas dedicated to rapeseeds, sunflowers and soybeans in CH are indicated in Tab. 17.3. Given the yields of methyl ester from each crop (Swiss Granum 2003), these data allow to evaluate the maximum theoretical biodiesel production in CH, if all these agricultural areas were dedicated to biodiesel production.

Tab. 17.3 Biodiesel production potential in CH from existing cultivated areas (Swiss Granum 2003).

Feedstocks	Rapeseeds	Sunflower seeds	Soybeans
Agricultural surface areas (ha)	16'000	5'500	2'530
Production (t/yr)	45'300	17'330	5'900
Biodiesel yield (l/t)	380	320	180
Biodiesel potential (Ml/yr)	17.2	5.5	1.1

The total potential amounts to 23.8 Ml, which represents less than 1.5% of the Swiss consumption of conventional diesel. Furthermore, all these surface areas are totally dedicated to the food industry, and there is hardly any room for biodiesel production from indigenous feedstocks, in Switzerland, in the present context. Imported feedstocks (i.e. rape seeds or directly vegetable oil), however, can contribute to increase the production of biodiesel in Switzerland significantly. This is indeed the situation in both production plants, in Geneva (Biocarb) and Etoy (EcoEnergie) at present.

Biodiesel can also be produced from waste cooking vegetable oil. According to Biocarb S.A., the consumption of vegetable oils and fats in Switzerland amounts to about 14.2 kg/cap.yr (data for 2001). Given a population of 7 million inhabitants, the annual consumption is close to 100’000 t/yr. Out of these 100’000 t, only 14’000 t have been recycled, corresponding to a recycling rate of 14%, much lower than that in neighbour countries (20% on average). Considering the likely improvement of the recycling rate to 20%, the potential of waste oil in Switzerland would approach 20’000 t/yr. Some of this waste oil is presently burnt in cement factories or regional incineration plants, the rest being either exported or recycled in industry. If all of this waste oil was to be converted to biodiesel, it would represent another 23.5 Ml/yr of biodiesel.

Overall, it appears that the global production potential of biodiesel in Switzerland is particularly limited compared to the national consumption of conventional diesel (approx. 1’800 Ml/yr).

There are currently two biodiesel producers in Switzerland, namely EcoEnergie Etoy (VD) and Biocarb (GE), the latter with a production capacity of over 5 Ml/yr from rape oil and waste cooking oil and the first 2.5 Ml/yr from rape seeds. Both production plants are considered as pilot scale facilities and actually benefit from a full tax exemption for pilot scale project (up to 5 Ml/yr). In order to give a better idea of what a commercial scale biodiesel production plant could look like in Switzerland, in the light of the previous potential considerations, it was agreed to consider a facility with a production capacity of 20-25 Ml/yr of biodiesel (see section 17.6). This capacity compares well with the average capacity of biodiesel plants in the EU, considering the relative scale of Switzerland. Such a production facility, however, would most likely have to rely on a significant share of imported feedstocks, given the potential of biodiesel production indicated above.

17.3 Characterisation of Energy Carrier

The present section aims at characterising the most significant physical and chemical characteristics of biodiesel as a fuel for transportation, such as the composition, density, energy content, etc. The distinction is made between oil and methyl ester, so that 'oil' here means the crude oil extracted from the biomass (via the oil mill), whereas 'methyl ester' refers to the esterified and purified oil which suits vehicle fuels requirements. The main characteristics of vegetable oils and methyl esters and treated waste vegetable cooking oil are given in Tab. 16.4 below.

Tab. 17.4 Main characteristics of vegetable oils and methyl esters.

		rape methyl ester	rape oil	soybean methyl ester	soybean oil	palm methyl ester	palm oil	palm kernel oil	vegetable oil methyl ester	refined vegetable oil, from waste
basic unit in the database		kg	kg	kg	kg	kg	kg	kg	kg	kg
Lower heating value (Hu)	MJ	37.2	37.2	37.2	37.2	37.2	37.2	37.2	37.2	36.8
Higher heating value (HHV)	MJ	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.1
Density 20°C	kg/l	0.888	0.918	0.870	0.922	0.870	0.918	0.918	0.888	0.916
Oxygen	kg	0.108	0.109	0.110	0.115	0.119	0.123	0.146	0.108	0.109
Carbon, fossil	kg	0.041	0.000	0.041	0.000	0.045	0.000	0.000	0.041	0.003
Carbon, biogen	kg	0.732	0.776	0.731	0.768	0.715	0.753	0.732	0.732	0.772
Hydrogen	kg	0.119	0.116	0.119	0.117	0.122	0.124	0.122	0.119	0.116
CO2 Factor	kg/MJ	0.0762	0.0764	0.0761	0.0757	0.0748	0.0742	0.0721	0.0762	0.0772
CO2 Factor	kg	2.8339	2.8435	2.8298	2.8158	2.7838	2.7599	2.6824	2.8339	2.8414
Formula		$C_{19}H_{35}O_2$	$C_{57}H_{102}O_6$	$C_{19}H_{35}O_2$	$C_{53}H_{98}O_6$	$C_{17}H_{33}O_2$	$C_{49}H_{97}O_6$	$C_{13}H_{27}O_2$	$C_{19}H_{35}O_2$	$C_{57}H_{102}O_6$
CAS		73891-99-3	8002-13-9		8001-22-7		8002-75-3	8023-79-8		

The main co-product of methyl esters, i.e. glycerine (CAS No. 00056-81-5, formula $C_3H_8O_3$), consists of 39.1% (wt.) C, 52.2% O and 8.7% H. As shown in Fig. 17.5, all of the carbon is biogenic. The lower heating value (LHV) of glycerine is 18.0 MJ/kg and its density at 20°C is 1.261 kg/l.

With the development of the European standard EN 14214, the minimum requirements on the quality of biodiesel were specified mutually at a European level by engine manufacturers and the biodiesel industry (see Tab. 17.5). The European standard has now become internationally acknowledged and is a guideline for the standardisation activities conducted by other countries (UFOP 2004).

Tab. 17.5 European standard for biodiesel, EN 14214.

Characteristics	Units	Limit values		Test procedures
		Min.	Max.	
Ester	% (wt./wt.)	96.50		pr EN14103
Density, @ 15°C	kg/m^3	860.00	900.00	EN ISO 3675 / EN ISO 12185
Kinematic viscosity, @ 40°C	mm^2/s	3.50	5.00	EN ISO 3104
Flash point, °C	°C	> 120		ISO/CD 3679
Sulphur content, % wt.	mg/kg		10.00	
Carbon residue (from 10% of distillation residue)	% (wt./wt.)		0.30	EN ISO 10370
Cetane index	-	51.00		EN ISO 5165
Ash (sulphurous ash)	% (wt./wt.)		0.02	ISO 3987
Water content	mg/kg		500.00	EN ISO 12937
Total pollution	mg/kg		24.00	EN 12662
Corrosive effect on copper (3h @ 50°C)	rating	1.00		DIN ISO 2160
Oxidation stability, 110°C	hr	6.00		pr EN 14112
Acid number	mg KOH/g		0.50	pr EN 14104
Iodine number	-		120.00	pr EN 14111
Linolenic acid	% (wt./wt.)		12.00	pr EN 14103
Polyunsaturated methyl ester (>3 double bonds)	% (wt./wt.)		1.00	
Methanol	% (wt./wt.)		0.20	pr EN 14110
Monoglyceride	% (wt./wt.)		0.80	pr EN 14105
Diglyceride	% (wt./wt.)		0.20	pr EN 14105
Triglyceride	% (wt./wt.)		0.20	pr EN 14105
Free glycerine	% (wt./wt.)		0.02	pr EN 14105
Total glycerine	% (wt./wt.)		0.25	pr EN 14105
Alkali metals (Na, K)	mg/kg		5.00	pr EN 14108 / pr EN 14108
Phosphorous content	mg/kg		10.00	pr EN 14107

The Cetane number or cetane index is a measure of the ignition quality of diesel fuel. Cetane ignites particularly well under high temperature and high pressure conditions. It is a long-chain hydrocarbon with 16 carbon atoms which does not require a pilot flame or an ignition spark and therefore is the ideal fuel for diesel engines. As a reference fuel it, is assigned a cetane number of 100. The higher the cetane number of a diesel fuel, the better the ignition and the combustion.

Available diesel fuels demonstrate a cetane number of 50-52 and the addition of ignition accelerators can increase the range to 53-54. Biodiesel compares well with mineral diesel with regard to its ignition qualities. Its key components are similar to cetane and so this fuel already has by nature a cetane number in the range 52-60. This easily complies with the requirements of the engine manufacturers (see Tab. 17.5) for high-quality fuel with good ignition qualities, without the need for additives.

It is generally applicable that biodiesel must be suitable for use in winter to temperatures of –20 °C (measured as the CFPP value) in the same way as mineral oil diesel. Both fuels receive additives to ensure this. Otherwise, an irreversible flocculation (production of paraffins) occurs in diesel fuel, which blocks the fuel lines, injection pump etc. If this happens, expensive cleaning is necessary. In contrast, biodiesel is only thickened which, in contrast to the paraffin precipitation of mineral oil diesel fuel, is reversible. When the temperature rises, biodiesel returns to a thinner state and it is unnecessary to clean the fuel system. Biodiesel on the basis of rapeseed oil has a CFPP value of approx. -10 to -12 °C without additives as a result of its raw materials.

The following characteristics of biodiesel are increasing its value as regards environmental aspects:

- Biodiesel only contains traces of sulphur and is thus especially suitable for diesel engines with catalysts. Oxidation catalysts in exhaust gas lines of diesel engines indeed reduce the emissions of CO, HC and particles. However, such catalysts may be seriously poisoned (and their efficiency deteriorated) by the sulphur contained in the exhaust gas. The sulphur content of biodiesel already corresponds to the legal demands of the EU for the year 2005.
- With an oxygen content of 11%, biodiesel improves the combustion properties of the mixture, thereby reducing certain polluting emissions such as CO and HC.
- Biodiesel is free of aromatics and already corresponds to the demands of the EU which should soon be valid.
- Biodiesel improves the lubricating properties of diesel fuels with a low sulphur content and it can substitute additives of fossil raw materials. Diesel engines can indeed be operated with markedly low emissions if the fuel shows an extremely low sulphur content. Low sulphur diesel with a content below 10 ppm is suitable for municipal areas even if very strict standards are to be applied. However, these fuels display very bad lubricating properties and can thus cause damages in the injection equipment. It has been proven that a blending of 2% of biodiesel suffices to reach the necessary lubricating property.
- One great environmental advantage of biodiesel is its rapid biodegradability. This advantage however requires particular attention regarding the stability of the fuel. If biodiesel is exposed to a specific "oxidation stress", i.e. high temperatures and frequent contact with (atmospheric) oxygen, or the influences of UV radiation or contact with non-ferrous metals, it ages faster than conventional diesel. In this case, the double bonds in the fatty acids of the biodiesel (see Fig. 17.5) are broken and they react with oxygen. That is the starting point for the polymerisation of the fuel, i.e. long-chained molecules form which thicken the fuel and lead to blockages in the injection pumps and filters. To completely prevent this effect, which occurs only under extreme conditions, environmentally friendly additives are added during the production of biodiesel, so-called antioxidants. Due to a lack of data, however, the use of antioxidants is not considered in the present dataset. Rape methyl ester (RME) has a naturally high resistance to oxidation. This must be preserved for as long as possible. A positive side effect: this also improves the storage stability and thereby the storage capability.

17.4 Use and Application of Energy Carrier

Biodiesel is an alternative fuel similar to conventional or ‘fossil’ diesel. Biodiesel can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. The process used to convert these oils to biodiesel is called ‘transesterification’. Most biodiesel produced in the EU today is produced from rapeseed oil, although waste vegetable oil sourced from restaurants, chip shops or industrial food is now used more and more often, its main advantage being the lower price of the raw oil. Depending on the country considered, waste vegetable oil can indeed often be sourced for free or sourced already treated for a small price. In Switzerland, waste vegetable oil is paid around 450-580 SFr/t (incl. delivery) to the collector/rectifier/refiner of waste oil (the waste oil must indeed be treated before conversion to biodiesel to remove impurities and water.

Technically, biodiesel can be used in place of or in addition (at any rate between 0 and 100%) to fossil diesel in conventional diesel engines, without any modification of the engine. Practically, not all car manufacturers guarantee a good functioning of their vehicles when fuelled with pure biodiesel or even with a blend of biodiesel and conventional diesel. In the EU, however, the norm EN 590 authorizes the addition of 5% biodiesel in any vehicle. Most German car manufacturers even offer warranties up to 100% biodiesel.

Biodiesel is an excellent solvent. When biodiesel is used in an engine that has been burning conventional diesel, a great deal of dirt and grime will be dislodged from the engine. Although this means that the fuel filter must be changed shortly after beginning to use biodiesel, the life of the engine can be increased due to the cleansing and lubricating properties of the fuel. For this reason, biodiesel use is growing as a diesel additive.

Biodiesel can degrade natural rubber hoses and gaskets because it is such a good solvent. These parts can be replaced in older vehicles and are not present at all in vehicles built since 1994. Blends of biodiesel and conventional diesel are often used with no engine modification.

Depending on the countries considered, the use of biodiesel as a vehicle fuel may change radically. In Germany for instance, biodiesel is used in place of conventional diesel, as neat biodiesel (often referred to as B100). In France, however, biodiesel is most often used as a blend of 30% biodiesel and 70% conventional diesel (B30). In the United States, it is B20 (20% biodiesel and 80% conventional diesel) that has become the most popular biodiesel-based blend.

The European standards for diesel fuel EN 590 and for gasoline EN 228 permit the addition of a maximum 5% biodiesel or bioethanol. While other mixtures containing a high proportion of biofuels are possible in sole tax terms, these mixtures no longer conform to either fuel standard and therefore have to be classified separately in accordance with the EU directive on the promotion of the use of biofuels. This aspect is particularly relevant in the case of the use of diesel/biodiesel mixtures with respect to the end customer (product liability), since the original quality of the fuels in question is impossible to determine in a mixture (Bockey 2004).

17.5 Description of the processes

The present section aims at defining the system described in this chapter, that is to say, biodiesel production. In order to well characterize the system(s) considered, biodiesel production is first described, after what the processes covered in this chapter and system boundaries will be defined precisely.

17.5.1 General considerations

The term “biodiesel” generally refers to methyl esters (sometimes called “fatty acid methyl ester” or yet FAME), produced by transesterification, a chemical process which reacts an oil or fat with methanol and a catalyst. Biodiesel from vegetable oil can be produced by a variety of esterification technologies, although most processes follow a similar basic approach (IEA 2004). Here, the process is divised into two main stages, namely (1) the extraction of oil from the feedstock (rape seeds, soybeans, palm fruit, etc.) or the refining of waste cooking oil, and (2) the esterification of the purified oil to methyl ester. The production process is described in details in the next paragraph.

17.5.2 Description of the production processes

The production of biodiesel from raw vegetable material requires several steps. First, raw oil is obtained either from pressing the feedstock in an oil mill or from treating the waste vegetable cooking oil in a waste oil treatment plant to remove impurities (i.e. solids and contaminants) and water. Then, the oil is esterified through a reaction with methanol, in the presence of a catalyst, in order to make the oil more appropriate for use in diesel engines. The various stages in the production process are now described.

Waste oil refining

Contrary to the commonly held viewpoint, used frying oil still contains many desirable components, which may be used in several ways. For example, it can be applied as an additive to feeds for farm animals, which enrich the diet nutritionally and make the feed more oily. Engines capable of burning used frying oil directly have been produced, but most research is being done on the production of methyl esters from the oil to yield biodiesel for subsequent blending with diesel (Buczek & Czepirski 2004).

The process of waste cooking oil refining for the subsequent production or vegetable oil methyl ester (VOME) involves mainly the coarse filtration of the oil and the removal of water and impurities. The presence of water, indeed, may cause ester saponification in the subsequent esterification process under alkaline conditions (Zhang 2003a). Saponification (i.e. formation of soaps) not only consumes the catalyst, but also the resulting soaps can cause the formation of emulsions, which create difficulties in downstream recovery and purification of methyl esters.

The refining of waste cooking oil for subsequent production of biodiesel also involves a pre-treatment step to remove the (undesirable) free fatty acids (FFA) contained in the oil. FFA can indeed react with an alkali catalyst to produce unwanted soaps and water. Usually the level of free fatty acids in waste cooking oil is greater than 2% wt. and needs to be reduced down to a maximum of 0.5% in order to optimize the production of methyl esters. This removal usually performed through a dilute-acid esterification process, where FFA are converted to esters (Zhang 2003a). The oil is reacted with methanol in the presence of sulfuric acid (which acts as a catalyst). Glycerine is employed as a liquid entraining agent to purify the oil.

Crude oil extraction

The two main processes for extracting oil from oil seeds are (1) mechanical press extraction and (2) solvent extraction.

In mechanical press (also referred to as cold press) extraction, the oil seeds are usually first heated to about 40-50°C and then crushed in a screw press. After most of the oil is removed, the remaining seed meal can be used as an animal feed. This is the technology used by EcoEnergie Etoy (CH) to extract the oil from the rape seeds.

The solvent process extracts more of the oil contained in the oil seed feedstock but requires more expensive equipment. The process uses a solvent (usually hexane) to dissolve the oil. After extraction, the oil is separated from the solvent by a distillation process. The solvent condenses and can be recycled and reused in the process. Solvent extraction shows a higher efficiency and also produces a vegetable oil with a higher degree of purity than the mechanical press process. This is the technology used in most large oil mills in the EU (Germany, France, Italy, Austria, etc.) and in the US.

Transesterification

As mentioned before, raw vegetable oils cannot usually be combusted in classic direct-injection diesel engines because they are too viscous to be sprayed, their volatility is low, and they burn incompletely, leaving engine deposits. Through the process of transesterification, the large branched triglycerides molecules are altered to become smaller, unbranched methyl ester molecules, which are comparable in size to the components of classic diesel fuel (see Fig. 17.5). This process of converting vegetable oils to their esters results in the complete removal of glycerides, and the lowering of the boiling point, flash point, and viscosity of the oil.

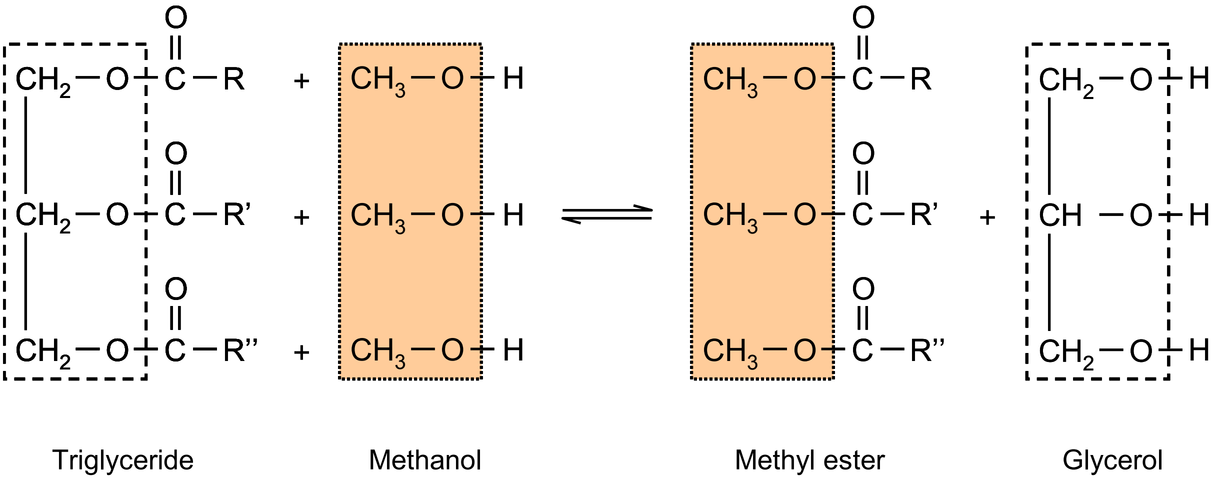

Fig. 17.5 The transesterification reaction.

There are three basic methods to biodiesel production, namely (1) base-catalyzed transesterification of the oil, (2) acid-catalyzed transesterification of the oil and (3) conversion of the oil to its fatty acids and then to biodiesel. Most of the biodiesel produced today is done with first option, i.e. the base-catalyzed reaction (it is the case in both biodiesel production plants in Switzerland today), and therefore it is the process that is considered in this study.

To produce biodiesel through this base-catalyzed reaction, the oil (mainly triglycerides, consisting of three long chain fatty acids attached to a glycerol backbone) is reacted with an alcohol (most generally methanol, because of its low cost and large availability) in the presence of an alkaly catalyst (most generally sodium hydroxide or potassium hydroxide which has already been mixed with the alcohol) to produce glycerol (or glycerine) and methyl esters or biodiesel (see Fig. 17.5).

The reaction mix of oil and catalyst is kept just above the boiling point of the alcohol to speed up the reaction. Recommended reaction time varies between 1 to 8 hours. Excess alcohol is normally used to ensure total conversion of the oil to its esters. After separation of the glycerol and biodiesel phases, the excess alcohol is removed with an evaporation process or by distillation.

17.6 Oil mill and vegetable oil esterification plant

17.6.1 System characterization

The two infrastructure processes ‘oil mill’ and ‘vegetable oil esterification plant’ (Fig. 17.6) are based on the biodiesel plant of EcoEnergie Etoy (CH), described in (Rinaldi & Hergé 1998).

Although the plant layout in Fig. 17.6 corresponds to a pilot plant in the CH context, the same process units and pieces of equipment are found in most oil mills and esterification plants in the world. Therefore, these datasets are applied to oil extraction and methyl ester production processes throughout the report.

As mentioned in paragraph 17.2.3, the production capacity of the mill and the esterification plant are adapted from the plant of EcoEnergie Etoy, to match the estimated biodiesel production potential in CH in the near future. The oil mill has a production capacity of 22’000 t/yr of vegetable oil (i.e. a feed capacity of about 60'000 t/yr of rape seeds), while the esterification plant has a production capacity of approx. 22’000 t/yr of methyl ester.

The actual life-cycle inventories of the oil mill and the esterification plant are described in details in paragraphs 17.6.2 and 17.6.3, respectively.

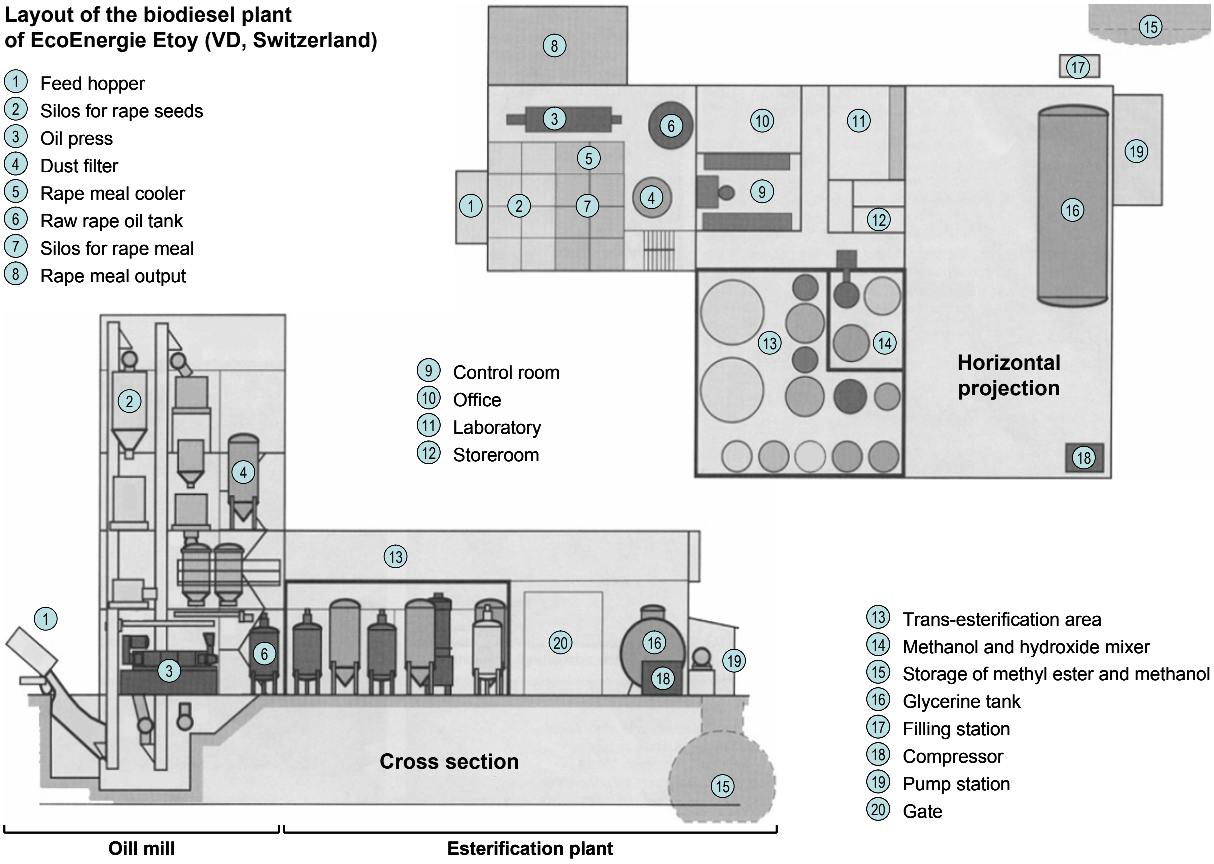

Fig. 17.6 Layout of the biodiesel plant iof EcoEnergie Etoy (VD Switzerland). Adapted from (Rinaldi & Hergé 1998).

17.6.2 LCI of ‘Oil mill, CH’

The unit process 'oil mill' is an infrastructure process. It includes land use, building and facilities as well as dismantling and elimination/recycling. As indicated in paragraph 17.2.3, it has a production capacity of 25 Ml of vegetable oil per year (i.e. 22'000 t/yr), corresponding to a feed capacity of about 60'000 t of rape seeds per year. The construction time and lifetime of the facility is taken as 2 and 50 years, respectively. The various elements considered within the oil mill include: rape seeds storage tank, feeder hopper, intermediate tank, drum screen, pre-grinder, conveying screw, oil mill, and raw oil tank (see Fig. 17.8) as well as offices and the building envelope.

The land occupation, building surface areas and volumes and equipment weight are adapted from (Rinaldi & Hergé 1998), which describes the facility of EcoEnergy in Etoy (VD). The oil mill in Etoy has a production capacity of 2.5 Ml/yr of rape oil, that is 10 times less than the oil mill considered here. Surface areas and equipment weight are therefore multiplied by 10 in order to describe the oil mill.

The resulting surface area for process units and offices is 5’670 m^2. With a storage capacity of 2 months and a surface area requirement of 0.2 m^2/t (Nemecek 2004), the land use for silos is taken as 2’000 m^2. The total space occupied is considered to be twice as large, resulting in an overall land use of 15’520 m^2. Land occupation for construction and operation are calculated by multiplying the land use by the construction time and lifetime, respectively.

The dataset ‘building, hall’ is used to take into account the building envelope for storage (2’000 m^2) and offices (500 m^2), and the dataset ‘building, hall, steel construction’ is considered for the envelope of other process units.

The weight of the equipment is estimated to be 738 t, i.e. 60% of the equipment weight in (Rinaldi & Hergé 1998) times 10 for scale correction (the other 40% being considered for the transesterification side). The dataset ‘steel, low alloyed, at plant’ is used for the equipment. Delivery on site (standard distances, i.e. 600 km by train and 50 km by 28t lorry) as well as end-of-life recycling is also taken into account. However, energy use and waste management occurring in the construction period are not taken into account due to lack of data.

The unit process raw data of 'oil mill' is indicated in Tab. 17.6.

17.6.3 LCI of ‘Vegetable oil esterification plant, CH’

The unit process ‘vegetable oil esterification plant' is an infrastructure process. It includes land use, building and facilities, as well as dismantling and elimination/recycling. Just like the oil mill, it has a production capacity of 25 Ml of rape methyl ester per year (i.e. 22'000 t/yr), corresponding to an equivalent feed capacity. The construction time and lifetime of the facility are taken as 2 and 50 years, respectively. The various elements considered within the esterification plant include: rape oil storage tank, storage tanks, mixers, transesterification reactor, decanter, filter (see Fig. 17.8), as well as offices and the building envelope.

The land occupation, building surface areas and volumes and equipment weight are adapted from (Rinaldi & Hergé 1998), which describes the facility of EcoEnergy in Etoy (VD). The esterification facility in Etoy has a production capacity of 2.5 Ml/yr of rape methyl ester, that is 10 times less than the plant considered here. Surface areas and equipment weight are therefore multiplied by 10 in order to describe the esterification plant.

The resulting surface area for process units and offices is 4’630 m^2. The total space occupied is considered to be twice as large, resulting in an overall land use of 9’260 m^2. Land occupation for construction and operation are calculated by multiplying the land use by the construction time and lifetime, respectively.

The dataset ‘building, hall’ is used to take into account the building envelope for offices (500 m^2), and the dataset ‘building, hall, steel construction’ is considered for the envelope of other process units.

The weight of the equipment is estimated to be 492 t, i.e. 40% of the equipment weight in (Rinaldi & Hergé 1998) times 10 for scale correction (the other 60% being considered for the oil extraction side). The dataset ‘steel, low alloyed, at plant’ is used for the equipment. Delivery on site (standard distances, i.e. 600 km by train and 50 km by 28t lorry) as well as end-of-life recycling are also taken into account. However, energy use and waste management occurring in the construction period are not taken into account due to lack of data.

The unit process raw data of 'esterification plant' is indicated in Tab. 17.6.

Tab. 17.6 Unit process raw data of the datasets ‘oil mill’ and ‘esterification plant’.

	Name	Location	InfrastructureProcess	Unit	oil mill	vegetable oil esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH			
	InfrastructureProcess				1	1			
	Unit				unit	unit			
product	oil mill	CH	1	unit	1.00E+0				
product	vegetable oil esterification plant	CH	1	unit		1.00E+00			
resource, land	Occupation, industrial area, built up	-	-	m2a	3.84E+5	4.63E+5	1	1.84	(3,5,1,1,4,na); Data from biodiesel producer in CH, industrial data
	Occupation, industrial area, vegetation	-	-	m2a	3.84E+5	2.32E+5	1	1.84	
	Occupation, construction site	-	-	m2a	3.07E+4	1.85E+4	1	1.84	
	Transformation, from unknown	-	-	m2	1.53E+4	9.26E+3	1	2.29	
	Transformation, to industrial area, built up	-	-	m2	7.67E+3	4.63E+3	1	2.29	
	Transformation, to industrial area, vegetation	-	-	m2	7.67E+3	4.63E+3	1	2.29	
technosphere	building, hall	CH	1	m2	2.50E+3	5.00E+2	1	3.28	
	building, hall, steel construction	CH	1	m2	5.17E+3	4.13E+3	1	3.28	
	steel, low-alloyed, at plant	RER	0	kg	7.38E+5	4.92E+5	1	1.58	
	transport, freight, rail	CH	0	tkm	4.43E+5	2.95E+5	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	3.69E+4	2.46E+4	1	2.09	

17.7 Oil and methyl ester from rape seeds, CH

17.7.1 System characterization

The system described in this paragraph includes (1) the production of rape oil (incl. distribution) and rape meal from rape seeds, and (2) the production of rape methyl ester and glycerine from rape oil, in the Swiss context (Fig. 17.7).

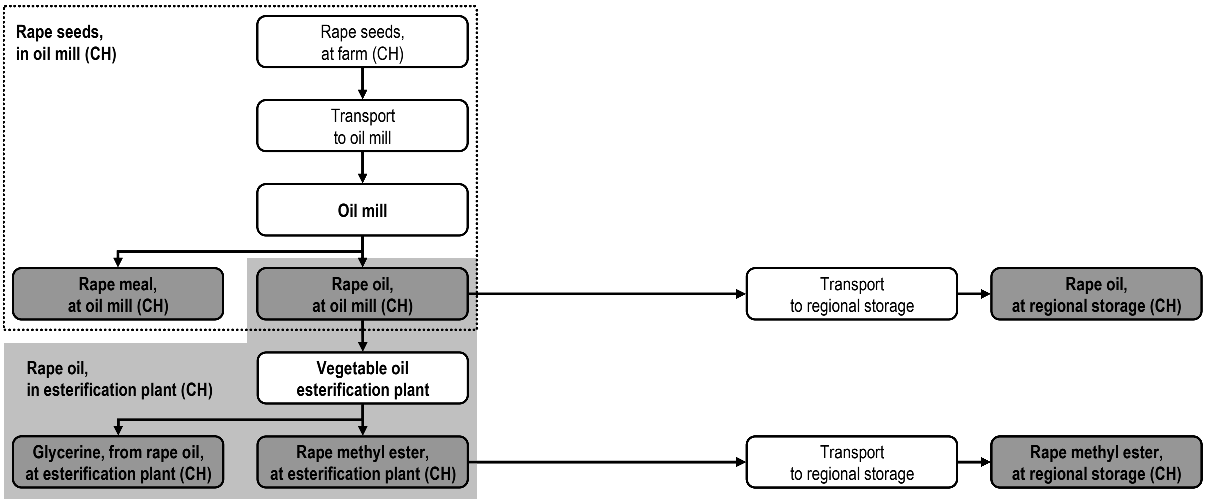

Fig. 17.7 Oil and methyl ester from rape seeds, CH: system definition and boundaries.

The processes shown in dark boxes indicate datasets actually described and developed in this chapter. The dashed line and the shaded area show the boundaries of the two multi-output (MO) processes 'Rape seeds, in oil mill' and 'Rape oil, in esterification plant' respectively. These two processes are described below. The infrastructure processes ‘Oil mill’ and ‘Vegetable oil esterification plant’ are treated in paragraph 17.6.2 and 17.6.3 respectively.

The system described in the Swiss context corresponds to the process as performed by EcoEnergie Etoy in its 2.5 Ml/yr biodiesel plant, situated in Etoy (Vaud, CH). A schematic representation of the process units is given in Fig. 17.8.

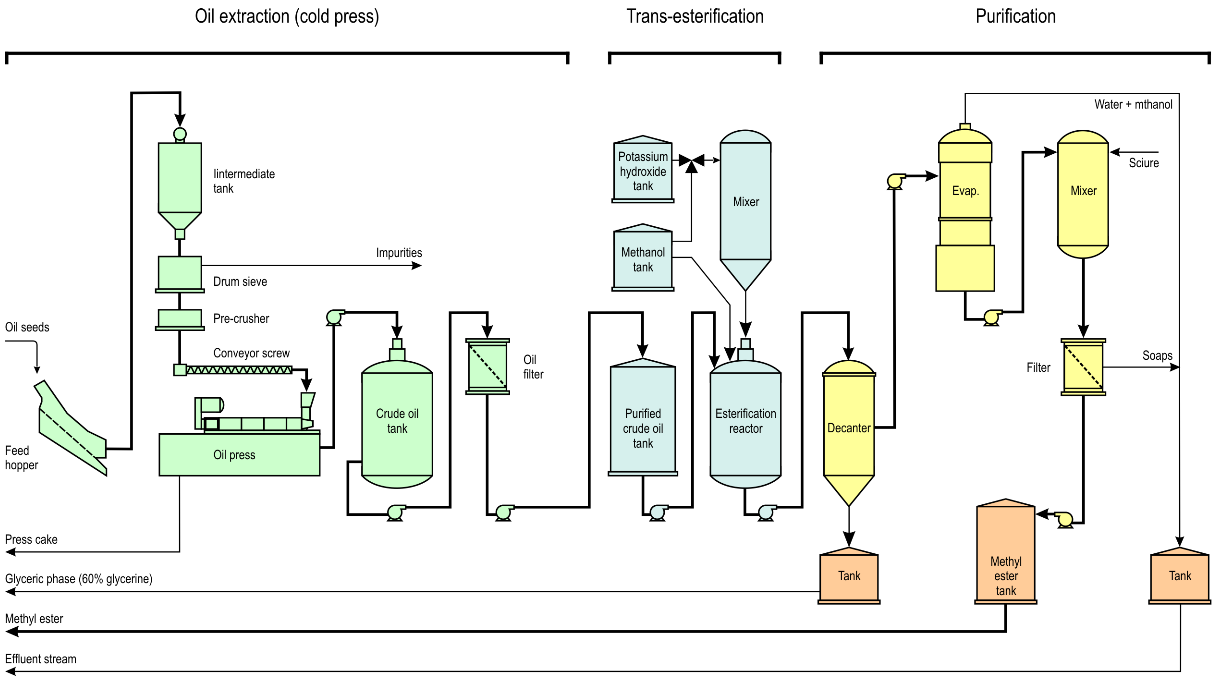

Fig. 17.8 Schematic representation of the biodiesel plant of EcoEnergie Etoy. Adapted from (Rinaldi & Hergé 1998).

Upon arrival at the oil mill, the seeds are sent to an intermediate tank via the feed hopper. Impurities are removed in a drum sieve. Rape seeds are then pre-crushed and directed towards the seed press for actual oil extraction. The techology employed is cold press extraction. The solid part of the seeds gives rise to a by-product referred to as rape meal, mostly used as animal feed. The crude oil is then filtered and stored on site.

Crude rape oil may be used in the food industry (as cooking oil or salad dressing), as a fuel for transport and/or heating purposes. The distribution of the oil to the end-user is described in the dataset ‘Rape oil, at regional storage’ (see paragraph 17.14.2).

The oil may also be further processed to produce rape methyl ester for transportation purposes. The oil is reacted with a mixture of methanol (fossil) and potassium hydroxide (catalyst) by transesterification, resulting in the production of methyl ester, according to the reaction given in Fig. 17.5.

Two side-reactions occur, namely: (1) neutralization (due to the presence of free fatty acids in the oil), and (2) saponification. Both of these reactions consume potassium hydroxide and result in the formation of soap (neutralization also produced water). The presence of water and soaps in the reactions product require subsequent purification in order to comply with the EN14214 biodiesel standard.

Most of the glycerine is first removed by decantation. At EcoEnergie Etoy, the glyceric phase leaving the decanter has a puritiy of 60% only and cannot be marketed as such. Today, it is actually shipped to the biodiesel plant in Geneva (Biocarb) where it is concentrated by evaporation and sold on the market as pure glycerine.

After the decantation stage, water, methanol and soaps need to be removed from the methyl ester. Water and methanol are evaporated (Fig. 17.8). The soaps and residual glycerine are then seperated from the esters by adding sawdust (on which the glycerine and soaps adsorb) which is then filtered and taken out. The slurry of soaps and glycerine used to be returned to farmed and spread over the fields as a fertilizer complement. Today, it is shipped to Geneva, together with the glyceric phase, for further treatment and concentration. The treatment is included in the present LCI (see paragraph 17.7.3). The purified methyl ester is stored on-site before distribution and/or shipping to regional storage.

The description of the production process as well as LCI data of this process are based communications from biodiesel producers in Switzerland[42], and on the desription in (Rinaldi & Hergé 1998) and (Dauriat et al. 2001).

The biodiesel plant in Etoy processes 6’700 t/yr of rape seeds and produces approx. 2’550 t/yr of rape oil and 4’180 t/yr of rape meal. Accordingly, 1 ton of rape seeds result in:

- 379.1 kg of rape oil;
- 620.9 kg of rape meal.

From the 2’550 t/yr of rape oil, the biodiesel plant in Etoy produces approx. 2’200 t/yr of rape methyl ester and 240 t/yr of glycerine (once treated in Geneva). Accordingly, 1 ton of rape oil results in:

- 863.6 kg of rape methyl ester;
- 93.3 kg of glycerine.

The allocation of environmental impacts in this study is performed according to the respective market prices of the by-products generated in the process. For reasons of consistency between the production of rape methyl ester in the Swiss and the European context, the same price levels are used in both cases. The calculation of the allocation factors in the CH context is illustrated in Fig. 17.9.

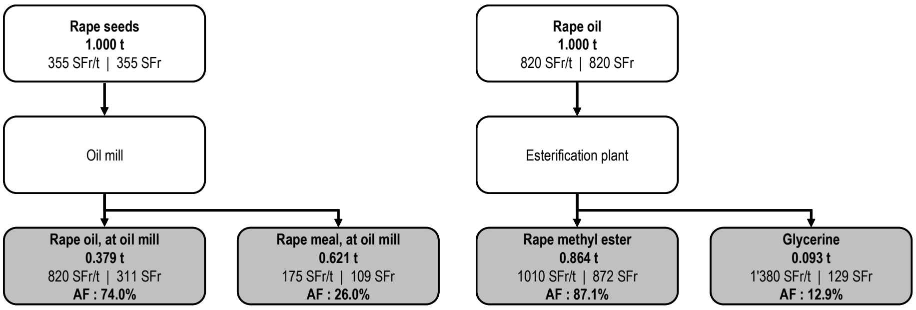

Fig. 17.9 Calculation of the allocation factors for the production of rape oil and methyl ester (CH).

The calculation above is based on the market prices of rape oil (820 SFr/t) and rape meal (175 SFr/t, as animal feed), as well as rape methyl ester (1’010 SFr/t) and glycerine (1’380 SFr/t). The prices quoted in Fig. 17.9 are adapted to the Swiss context from German prices in the biodiesel industry (Schöpe & Britschkat, 2002). The allocation factor is 74.0% to rape oil (i.e. 26.0% to rape meal) as far as the oil mill is concerned, and 87.1% to rape methyl ester (i.e. 12.9% to glycerine) in esterification.

Although the economic allocation is the method applied for this dataset, other methods could be applied, including allocation according to the energy content, mass or yet carbon balance. The allocation factors for the various methods are indicated in Tab. 17.7.

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[42] Personal communication of Eric Hergé (EcoEnergie Etoy) and François Fleury (Biocarb), 2005.

Tab. 17.7 Allcoation factors for the datasets relating to the production of rape methyl ester (CH).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Oil mill	Rape oil	74.0%	58.2%	37.9%	40.1%
	Rape meal	26.0%	41.8%	62.1%	59.9%
Esterification plant	Rape methyl ester	87.1%	95.0%	90.2%	94.5%
	Glycerine	12.9%	5.0%	9.8%	5.5%

In order to evaluate the allocation factor with respect to the energy content, heating values for rape oil, rape meal, rape methyl ester and glycerine are taken as 37.2, 16.3, 37.2 and 18 MJ/kg, respectively. Mass allocation factors are derived from the mass balance as indicated in Tab. 17.7. Finally, allocation with respect to the carbon content is calculated from the initial carbon content of rape seeds (62% wt. carbon) and the generic chemical formulas of rape oil ($C_{57}H_{102}O_6$), rape methyl ester ($C_{19}H_{35}O_2$) and glycerine ($C_3H_8O_3$). The carbon content of rape meal is obtained by difference.

17.7.2 LCI of 'Rape seeds, in oil mill, CH'

The production of rape oil and rape meal from rape seeds in the CH context is described in details in paragraph 17.7.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

Unless stated otherwise, the data below is from (Hergé 2005) or (Rinaldi & Hergé 1998), and is given per ton of rape seeds.

Rape seeds are transported from the farm to the oil mill over an average distance of 100 km on road, by 16t lorry (assumption due to the lack of data concerning the supply of rape seeds). The shares of IP, extensive and organic rape seeds are considered to match the present structure of rape production in Switzerland in 2004, i.e. 71%, 28% and 1% respectively[43].

As far as energy is concerned, the electricity consumed in the process amounts to 62 kWh per ton of rape seeds. As opposed to most oil mills and biodiesel facilities, the process in Etoy is all-electric due to the relative small size of the plant (pilot scale).

Raw materials used in the process are limited to phosphoric acid (0.357 kg). According to the ecoinvent guidelines, average transport distances are used for the delivery of raw materials to the oil mill. They include 50 km by 28t lorry and 600 km by train. These values are applicable of Switzerland.

The infrastructure is described in the 'oil mill' dataset (paragraph 17.6.2), with an annual feed capacity of 60'000 t/yr (i.e. 22'000 t/yr of oil) over a lifetime of 50 years, i.e. 3.33E-7 units per ton of seeds.

Carbon dioxide input and emissions are considered to satisfy the carbon balance amongst the various products in spite of the economic allocation. Indeed, because the economic allocation is applied, rape oil (through rape seeds) benefits from a CO_2 credit which is larger than its actual carbon content (allocation of 74% of the rape seeds to rape oil). In order to satisfy the carbon balance between the two outputs (rape oil and rape meal), a (fictive) CO_2 output of 910 kg per ton of rape seeds is taken into account (in addition to the actual CO_2 emissions, according to carbon balance) and allocated to rape oil. In order to balance CO_2 emissions, a (ficitve) CO_2 input (as resource, from air) of the same amount (910 kg/t) is also included and allocated to rape meal, according to its carbon content. The same approach is applied throughout the chapter in order to allocate the correct carbon credit to each product in multi-output (MO) processes, according to its actual carbon content.

Waste heat (893 MJ) is calculated according to the electricity use and energy balance over the process.

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[43] Personal communication of Cornelia Stettler (Carbotech) 25.05.05, based on BLW statistics.

The two outputs of the MO-process ‘rape seeds, in oil mill, CH’ include:

- ‘rape oil, at oil mill, CH’: **379.1 kg/t rape seeds**;
- ‘rape meal, at oil mill, CH’: **620.9 kg/t rape seeds**;

The economic allocation approach (paragraph 17.6, Tab. 17.7) is used, with allocation factors of 74.0% and 26.0% respectively (applicable to common stages, including the feedstock).

The unit process raw data of 'rape seeds, in oil mill' is indicated in Tab. 17.8.

Tab. 17.8 Unit process raw data of the dataset ‘rape seeds, in oil mill’, CH.

	Name	Location	InfrastructureProcess	Unit	rape seeds, in oil mill	rape oil, at oil mill	rape meal, at oil mill	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	rape oil, at oil mill	CH	0	kg	3.79E-1	1.00E+02				
product	rape meal, at oil mill	CH	0	kg	6.21E-1		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	9.10E-1	0	1.00E+2	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
technosphere	rape seed IP, at farm	CH	0	kg	7.10E-1	7.40E+1	2.60E+1	1	1.07	(1,1,1,2,1,3); Industrial data from biodiesel producer in CH
	rape seed extensive, at farm	CH	0	kg	2.80E-1	7.40E+1	2.60E+1	1	1.07	
	rape seed, organic, at farm	CH	0	kg	1.00E-2	7.40E+1	2.60E+1	1	1.07	
	electricity, medium voltage, at grid	CH	0	kWh	6.20E-2	7.54E+1	2.46E+1	1	1.07	
	transport, freight, rail	CH	0	tkm	2.14E-4	7.40E+1	2.60E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.79E-5	7.40E+1	2.60E+1	1	2.09	
	transport, lorry 16t	CH	0	tkm	1.00E-1	7.40E+1	2.60E+1	1	2.09	
	oil mill	CH	1	unit	3.33E-10	7.40E+1	2.60E+1	1	3.27	(1,1,1,1,4,5); Calculation, according to feed capacity and lifetime of the plant
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	3.57E-4	7.40E+1	2.60E+1	1	1.07	(1,1,1,2,1,3); Literature data & industrial data from biodiesel producer in CH
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	9.19E-1	1.00E+2	0	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
	Heat, waste	-	-	MJ	8.93E-1	7.40E+1	2.60E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.7.3 LCI of ‘Rape oil, in esterification plant, CH’

The production of methyl ester and glycerine from rape oil in the CH context is described in details in paragraph 17.7.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

Unless stated otherwise, the data below is from a personal communication of a biodiesel producer in Switzerland[44] or (Rinaldi & Hergé 1998), and is given per ton of rape oil.

The esterification plant being attached to the oil mill (Fig. 17.6), there is no transport of rape oil. Some transport, however, is considered for the post-treatment of glycerine and liquid effluents, since these are treated in Geneva (see paragraph 17.6). A transport distance of 45 km by 28t lorry is considered.

As far as energy is concerned, the electricity consumed in the process amounts to 73.5 kWh per ton of rape oil. The process in Etoy is all-electric due to the relative small size of the plant (pilot scale).

Raw materials include methanol (134.8 kg), potassium hydroxide (13.8 kg) and sawdust (0.135 kg, i.e. 4.72E-4 m^3 given a bulk density of 287.3 kg/m^3). Average transport distances are used for the delivery of raw materials, including 50 km by 28t lorry and 600 km by train.

The consumption of water amounts to 27.3 kg per ton of rape oil. Liquid effluents from methyl ester purification and glycerine treatment amount to 0.219 m^3.

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[44] Personal communication of Eric Hergé (EcoEnergie Etoy), 2005.

The infrastructure is described in the ‘vegetable oil esterification plant’ dataset (see paragraph 17.6.3), with an annual feed capacity of 22’000 t/yr over a lifetime of 50 years, i.e. 9.09E-7 units per ton of oil.

Carbon dioxide emissions (391 kg) are considered to close the carbon balance. These correspond to carbon present in the waste stream, considered to end up as CO_2. Waste heat (6’360 MJ) is calculated according to the consumption of electricity and energy balance over the process.

The two outputs of the MO-process ‘rape oil, in esterification plant, CH’ include:

- ‘rape methyl ester, at oil mill, CH’: **863.6 kg/t rape oil**;
- ‘glycerine, from rape oil, at oil mill, CH’: **93.3 kg/t rape oil**;

The economic allocation approach (paragraph 17.6, Tab. 17.7) is used, with allocation factors of 87.1% and 12.9% respectively (applicable to common stages, including the feedstock). The unit process raw data is indicated in Tab. 17.9.

Tab. 17.9 Unit process raw data of the dataset ‘rape oil, in esterification plant’, CH.

	Name	Location	InfrastructureProcess	Unit	rape oil, in esterification plant	rape methyl ester, at esterification plant	glycerine, from rape oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	rape methyl ester, at esterification plant	CH	0	kg	8.636E-01	1.00E+02				
product	glycerine, from rape oil, at esterification plant	CH	0	kg	9.327E-02		1.00E+02			
technosphere	rape oil, at oil mill	CH	0	kg	1.00E+0	8.71E+1	1.29E+1	1	1.21	(1,2,1,1,1,5); Industrial data from biodiesel producer in CH
	methanol, at regional storage	CH	0	kg	1.35E-1	8.71E+1	1.29E+1	1	1.07	(1,1,1,2,1,3); Industrial data from biodiesel producer in CH
	electricity, medium voltage, at grid	CH	0	kWh	7.35E-2	8.71E+1	1.29E+1	1	1.07	
	transport, freight, rail	CH	0	tkm	8.92E-2	8.71E+1	1.29E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	2.15E-2	8.71E+1	1.29E+1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	8.71E+1	1.29E+1	1	3.05	(1,2,1,1,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	CH	0	kg	2.73E-2	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Literature, environmental
	sawdust, Scandinavian softwood (plant-debarked), u=70%, at plant	ꓘORDE	0	m3	4.70E-7	8.71E+1	1.29E+1	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	potassium hydroxide, at regional storage	RER	0	kg	1.38E-2	8.71E+1	1.29E+1	1	1.07	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	2.19E-4	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.91E-1	4.06E+1	5.94E+1	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	6.36E+0	8.71E+1	1.29E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.8 Oil and methyl ester from rape seeds, RER

17.8.1 System characterization

The system described in this paragraph includes (1) the production of rape oil and rape meal from rape seeds, and (2) the production of rape methyl ester and glycerine from rape oil, in the European context (Fig. 17.10).

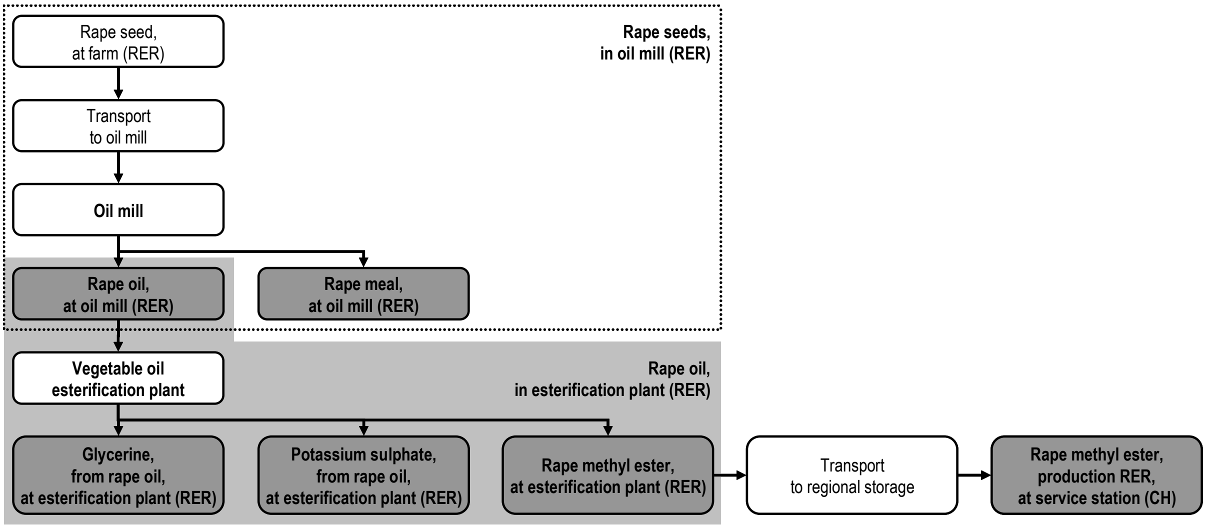


Fig. 17.10 Oil and methyl ester from rape seeds, RER: system definition and boundaries.

The system described in the European context corresponds to the process in a standard medium-to-large scale biodiesel plant. Although the plant is large, the process is quite similar to that in Etoy (CH). The main differences (incl. technology and yields) are discussed below.

As mentionned before, rape oil can be readily obtained by pressing the seed without prior conditioning (see paragraph 17.5.2). While solvent extraction can produce significantly higher yields, the cold-press technology employed in Etoy (CH, Vaud) is simpler and cheaper. Therefore, smaller-scale, farm-based biodiesel production likely would employ the simple cold-press method, while larger-scale and more sophisticated production settings might favour the use of higher yield extraction techniques such as solvent extraction.

The technology considered for oil extraction in the EU context involves a solvent extraction system to produce oil from the crushed seeds, using n-hexane as the solvent. Most of the solvent is recycled, but approximately 2.8 kg of hexane per ton of raw oil (i.e. 1.1 kg per ton rape seeds processed) are lost due to the high volatility of the solvent. Like in the case of cold-press-extraction, the rape meal is obtained as a by-product of rape oil, in similar proportions.

Once obtained, the raw oil is filtered, collected in a tank, and then periodically pumped into an agitating transesterfication reactor (see Fig. 17.11). In the reactor, the oil is heated to 60-70°C, and gradually brought into contact with a mixture of sodium hydroxide (NaOH) and methanol. The mixture used is typically 10% NaOH by weight. Potassium hydroxide (KOH) can be used in place of NaOH. However, NaOH has a lower molecular weight than KOH, so smaller amounts are required, it is cheaper and its salts are less soluble in methyl esters than are those of KOH. After an hour of agitation, the mixture is allowed to separate into an upper layer of methyl esters and a lower layer of glycerine diluted with active methanol. The unreacted methanol is then air-stripped or vacuum distilled away, and then the methyl esters are again mixed with methanol, and allowed to react for 30 minutes. Finally, the excess methanol is again removed.

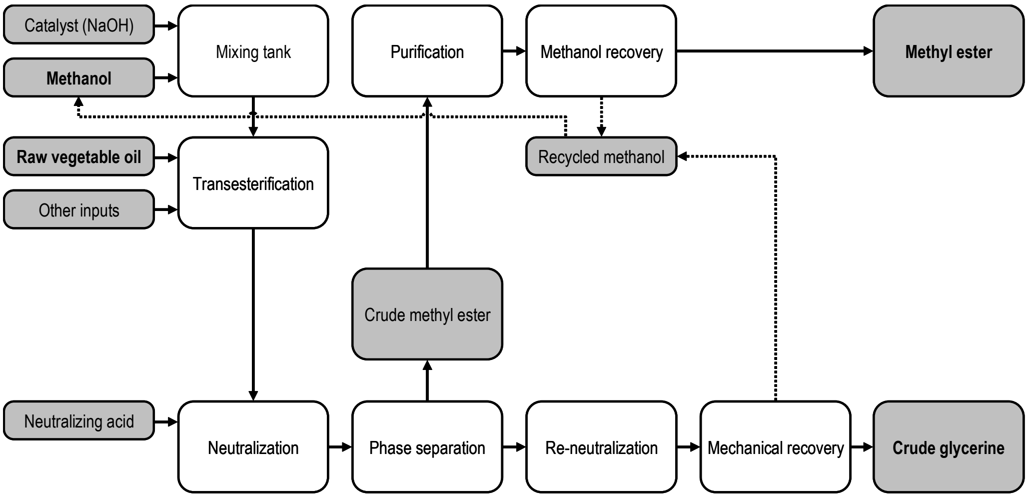


Fig. 17.11 Schematic diagram of the transesterification process.

After transfer from the transesterfication reactor to the finishing reactor, small amounts of concentrated phosphoric acid (H_3PO_4) are added to the raw methyl esters to break catalyst residues and sodium soaps. Ammonium hydroxide (NH_4OH) is then added to neutralize any remaining free fatty acids or phosphoric acid. Excess ammonia (NH_3) is then air-stripped, and finally the esters are centrifuged to remove any solidified components. Conversion rates of up to 99% have been obtained with this two-step method. It has also successfully been used for waste cooking oil.

Fig. 17.12 illustrates the arrangement of the various process units in the esterification plant. The flows of the different resources consumed along the process are also indicated on the diagram. The figure is adapted from (Zhang, 2003a).

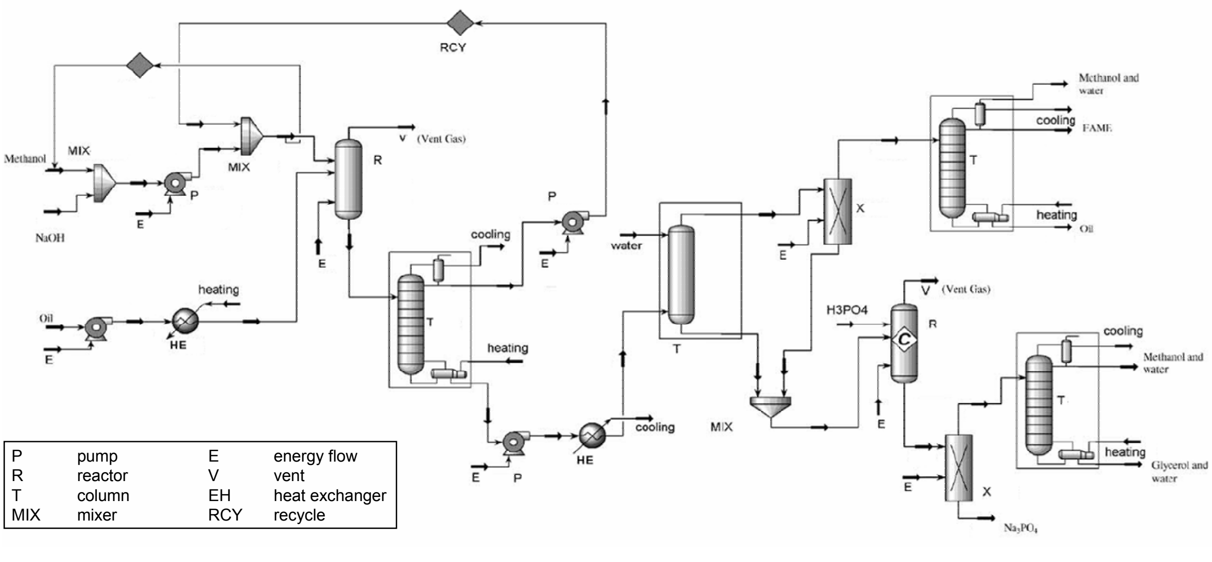


Fig. 17.12 Process units in the esterification plant. Adapted from (Zhang 2003a) © Elsevier 2003.

The methyl ester production process described above uses raw rapeseed oil, methanol, NaOH, H_3PO_4, NH_4OH and water, and produces methyl ester, raw glycerine, and sodium phosphate (Na_3PO_4). If potassium hydroxide (KOH) is used instead of sodium hydroxide (NaOH), the resulting salt is potassium phosphate. Liquid effluent consists of approximately 30-40% free fatty acids and 60-70% methyl esters and are ausually eliminated in a local wastewater treatment plant.

According to (O'Connor 2004a; EBB 2005; UFP 2004), the average production capacity of biodiesel plants is 50 kt/yr in Germany (30 in operation, 5-10 under construction or projected), 75 kt/yr in Italy (7 in operation, 2 closed down) and 90 kt/yr in France (6 in operation). An average mill in the EU thus processes some 65'000 t/yr of rape seeds and produces approx. 64'000 t/yr of rape oil and 98'000 t/yr of rape meal. Accordingly, 1 ton of rape seeds result in:

- 395.6 kg of rape oil;
- 604.4 kg of rape meal.

From the 64'000 t/yr of rape oil, a biodiesel plant in the EU context produces approx. 62'500 t/yr of rape methyl ester, 7'000 t/yr of glycerine and 1'100 t/yr of phosphate salt (although not oll plant sell the salts on the market). Accordingly (see Tab. 17.13), 1 ton of rape oil results in:

- 972.7 kg of rape methyl ester;
- 106.1 kg of glycerine;
- 16.4 kg of potassium phosphate.

The allocation of environmental impacts in this study is performed according to the respective market prices of the by-products generated in the process. For reasons of consistency between the production of rape methyl ester in the Swiss and the European context, the same price levels are used in both cases. The calculation of the allocation factors in the CH context is illustrated in Fig. 17.13.

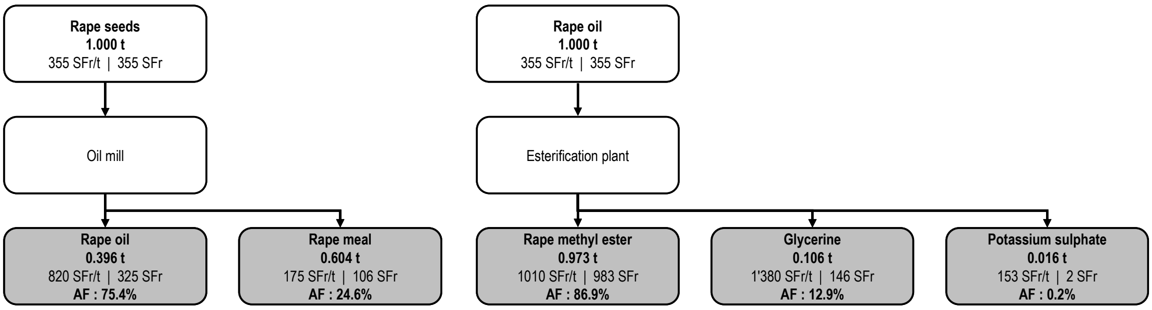


Fig. 17.13 Calculation of the allocation factors for the production of rape oil and methyl ester (CH).

The calculation above is based on the market prices of rape oil (820 SFr/t) and rape meal (175 SFr/t, as animal feed), as well as rape methyl ester (1'010 SFr/t), glycerine (1'380 SFr/t) and potassium phosphate (153 SFr/t). The prices quoted in Fig. 17.13 correspond to the German situation in the biodiesel industry (Schöpe & Britschkat, 2002). The allocation is 75.4% to rape oil (i.e. 24.6% to rape meal) as far as the oil mill is concerned, and 86.9% to rape methyl ester, 12.9% to glycerine and 0.2% to potassium phosphate) in the esterification process.

Although the economic allocation is the method applied for this dataset, other methods could be applied, including allocation according to the energy content, mass or yet carbon balance. The allocation factors for the various methods are indicated in Fig. 17.13.

Tab. 17.10 Allcoation factors for the datasets relating to the production of rape methyl ester (RER).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Oil mill	Rape oil	75.4%	59.9%	39.6%	41.8%
	Rape meal	24.6%	40.1%	60.4%	58.2%
Esterification plant	Rape methyl ester	86.9%	95.0%	88.8%	94.5%
	Glycerine	12.9%	5.0%	9.7%	5.5%
	Potassium sulphate	0.2%	0.0%	1.5%	0.0%

17.8.2 LCI of 'Rape seeds, in oil mill, RER'

The production of rape oil and rape meal from rape seeds in the EU context is described in details in paragraph 17.8.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

All material and energy flows in Tab. 17.11 are indicated in reference to 1 ton of rape seeds. The values used in the inventory are given in the last column "ecoinvent". The figures in each case are calculated as the average of the data in the shaded boxes. When the data showed significant deviation with the trend of values or when the data was judged incoherent with other values (e.g. older data, different scale of facility, data refers to a larger system or a different energy supply structure, etc.), they were not included in the calculation of the average. Finally, the lines with no shaded box are the result of a sum for mass or energy balance purposes. Effluents are calculated in order to close the mass balance.

Tab. 17.11 Literature review of mass and energy balance of oil extraction from rape seeds.

		Jossart 2003	Mortimer 2003	LBST 2002	Wörtegger 1999	Scharmer 1996	Ceuteurik 1997	Kraus 1999	Dreier 2000	Schlöpe 2002	Calzoni 2001	ecoinvent
Oil extraction												
Inputs												
Rapeseeds	**kg**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**
Phosphoric acid	kg		0.4						0.3			**0.3**
Bentonite	kg		2.2					2.4	2.4			**2.3**
Hexane	kg		1.0	1.0		1.2	1.5	1.3	0.7			**1.1**
Electricity (press)	kWh		31.9	34.0		37.8	45.0	55.0	35.0			**39.6**
Electricity (refining)	kWh		1.1	2.5			3.8	2.4	2.4			**2.4**
Steam	MJ		693.9	709.6				694.1				**707.7**
Total inputs	kg	1000.0	1003.5	1001.0	1000.0	1001.2	1001.5	1003.7	1003.5			**1003.8**
Outputs												
Rape meal	kg	612.3	599.5	591.7	628.9	602.7	616.0	593.0	592.4	602.0	601.6	**604.4**
Rape oil	kg	387.7	400.5	408.3	371.1	397.3	384.0	407.0	407.6	398.0	398.4	**395.6**
Effluent	kg		2.6					2.4	2.8			**2.7**
Hexane (vapours)	kg		1.0	1.0		1.2	1.5	1.3	0.7			**1.1**
Total outputs	kg	1000.0	1003.5	1001.0	1000.0	1001.2	1001.5	1003.7	1003.5	1000.0		**1003.8**

Unless stated otherwise, the data below is given per ton of rape seeds.

Rape seeds are transported from the farm to the oil mill over an average distance of 100 km on road, by 16t lorry (assumption due to the lack of data concerning the supply of rape seeds).

In accordance with the data in Tab. 17.11, the energy used per ton of rape seeds amounts to 42 kWh of electricity (39.6 kWh for oil extraction and 2.5 kWh for oil refining) and 708 MJ of steam from gas combustion.

Raw materials consumed within the process include phosphoric acid (0.355 kg), bentonite (2.343 kg) and hexane (1.100 kg). According to the ecoinvent guidelines, average transport distances are used for the delivery of raw materials to the oil mill. They include 100 km by 32t lorry and 600 km by train. These values are applicable of the EU.

The infrastructure is described in the 'oil mill' dataset (paragraph 17.6.2), with an annual feed capacity of 60'000 t/yr (i.e. 22'000 t/yr of oil) over a lifetime of 50 years, i.e. 3.33E-7 units per ton of seeds.

Hexane is considered to be emitted to the atmosphere and emissions are therefore equal to the amount of hexane make-up (i.e. 1.100 kg).

Carbon dioxide input and emissions (902 kg) are considered to satisfy the carbon balance amongst the various products in spite of the economic allocation. Waste heat (477 MJ) is calculated according to the consumption of electricity and energy balance over the process.

The two outputs of the MO-process 'rape seeds, in oil mill, RER' include:

- 'rape oil, at oil mill, RER': **395.6 kg/t rape seeds**;
- 'rape meal, at oil mill, RER': **604.4 kg/t rape seeds**;

The economic allocation approach (paragraph 17.6, Tab. 17.10) is used, with allocation factors of 75.4% and 25.6% respectively (applicable to common stages, including the feedstock). The unit process raw data is indicated in Tab. 17.12.

Tab. 17.12 Unit process raw data of the dataset 'rape seeds, in oil mill', RER.

	Name	Location	InfrastructureProcess	Unit	rape seeds, in oil mill	rape oil, at oil mill	rape meal, at oil mill	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	rape oil, at oil mill	RER	0	kg	3.956E-1	1.00E+02				
product	rape meal, at oil mill	RER	0	kg	6.044E-1		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	9.02E-1	0	1.00E+2	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
technosphere	rape seed conventional, at farm	DE	0	kg	1.00E+0	7.54E+1	2.46E+1	1	1.07	(1,1,1,2,1,3); Data from literature survey (1998-2006) & biodiesel producers
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	4.20E-2	7.67E+1	2.33E+1	1	1.09	(2,1,1,2,1,3); Data from literature survey (1998-2006) & biodiesel producers
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	7.08E-1	7.54E+1	2.46E+1	1	1.09	
	transport, freight, rail	RER	0	tkm	2.28E-3	7.54E+1	2.46E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	3.80E-4	7.54E+1	2.46E+1	1	2.09	
	transport, lorry 16t	RER	0	tkm	1.00E-1	7.54E+1	2.46E+1	1	2.09	
	oil mill	CH	1	unit	3.33E-10	7.54E+1	2.46E+1	1	3.28	(1,4,1,3,4,5); Calculation, according to feed capacity and lifetime of the plant
	bentonite, at processing	DE	0	kg	2.34E-3	7.54E+1	2.46E+1	1	1.10	(2,3,1,2,1,3); Data from literature survey (1998-2006) & biodiesel producers
	hexane, at plant	RER	0	kg	1.10E-3	7.54E+1	2.46E+1	1	1.09	
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	3.55E-4	7.54E+1	2.46E+1	1	1.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	2.70E-6	7.54E+1	2.46E+1	1	1.56	(5,5,1,2,1,na); Calculation to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	9.02E-1	1.00E+2	0	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
	Heat, waste	-	-	MJ	4.77E-1	7.54E+1	2.46E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Hexane	-	-	kg	1.10E-3	7.54E+1	2.46E+1	1	1.50	(1,1,1,2,1,3); Emissions are taken to be equal to input of gas

17.8.3 LCI of 'Rape oil, in esterification plant, RER'

The production of methyl ester and glycerine from rape oil in the CH context is described in details in paragraph 17.8.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

Tab. 17.13 Literature review of mass and energy balance of vegetable oil esterification to methyl ester.

		Jossart 2003	Mortimer 2003	LBST 2002	Wörtegger 1999	Scharmer 1996	Schlöpe 2002	Adami 2003	Heinzer 2000	Calzoni 2001	Zhang 2003	Dreier 1998	Borken 1999	ecoinvent
Transesterification														
Inputs														
Rape oil	**kg**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**	**1000.0**
Methanol	kg	100.0	103.6	99.7	110.0	108.0		108.9	152.2	106.3	111.6	104.8	108.0	**110.5**
Acids				0.1				5.0		1.0	7.8	7.8	5.1	**4.5**
Hydroxides	kg		11.4	20.9		5.9		7.9	15.5	5.9	9.5	12.0	8.6	**11.0**
Water	kg										26.0			**26.6**
Electricity	kWh		21.9	12.4		45.6		12.5	89.4	72.9		29.1	45.6	**41.1**
Steam	MJ			1252.7		553.0		701.9				583.7	1350.0	**898.6**
Total inputs	kg	1100.0	1115.0	1120.8	1110.0				1167.7	1114.3	1162.8	1132.4	1126.7	**1155.5**
Outputs														
Glycerine	kg	100.0	95.1	106.1	110.0	115.0	90.0	107.9	98.5	102.4	107.9	126.9	114.8	**106.1**
Potassium phosphate	kg						20.0				13.1			**16.4**
Effluent	kg		69.4	103.0				15.8	93.6	36.2	50.0	43.9	21.9	**58.7**
Rape methyl ester	kg	1000.0	950.6	911.6	1000.0	990.0	1000.0	990.1	975.6	975.6	952.3	961.5	990.0	**972.7**
Total outputs	kg	1100.0	1115.0	1120.7	1110.0				1167.7	1114.3	1155.0	1132.4	1126.7	**1155.5**

Various literature sources indicate different hydroxide catalysts. Here, the consumptions of catalysts are aggregated and shown as "Hydroxides" in Tab. 17.13. In the present dataset, the use of hydroxide is limited to potassium hydroxide. Similarly, acids are considered as phosphoric acid.

Unless stated otherwise, the data below is given per ton of rape oil.

Again, the esterification is supposed to be attached to the oil mill and hence, no transport is considered for rape oil.

In accordance with the data in Tab. 17.13, the energy used per ton of rape oil amounts to 41.1 kWh of electricity and 899 MJ of steam from natural gas combustion.

Raw materials used in the process include methanol (110.5 kg), potassium hydroxide (11.0 kg) and phosphoric acid (4.5 kg). Average transport distances are used for the delivery of raw materials, including 100 km by 32t lorry and 600 km by train.

The consumption of water amounts to 26.6 kg per ton of rape oil. Liquid effluents from methyl ester purification and glycerine treatment amount to 0.061 m^3.

The infrastructure is described in the 'vegetable oil esterification plant' dataset (see paragraph 17.6.3), with an annual feed capacity of 22'000 t/yr over a lifetime of 50 years, i.e. 9.09E-7 units per ton of oil.

The biogenic carbon present in the waste streams is considered to end up as CO_2 after treatment. These emissions are calculated in order to close the carbon balance and amount to 80 kg per ton of oil. A correction of 141 kg (input and output) is applied to satisfy the carbon balance (based on the carbon content) between methyl ester, glycerine and phosphate salts in spite of the economic allocation. Waste heat to air (1'460 MJ) is calculated to close the energy balance.

The three outputs of the MO-process 'rape oil, in esterification plant, RER' include:

- 'rape methyl ester, at esterification plant, RER': **863.6 kg/t rape oil**;
- 'glycerine, from rape oil, at esterification plant, RER': **93.3 kg/t rape oil**;
- 'potassium phosphate, from rape oil, at esterification plant, RER': **16.4 kg/t rape oil**;

The economic allocation approach (paragraph 17.6, Tab. 17.10) is used, with allocation of 86.9%, 12.9% and 0.2% respectively (applicable to common stages, including the feedstock). The unit process raw data is indicated in Tab. 17.14.

Tab. 17.14 Unit process raw data of the dataset ‘rape oil, in esterification plant’, RER.

	Name	Location	InfrastructureProcess	Unit	rape oil, in esterification plant	rape methyl ester, at esterification plant	glycerine, from rape oil, at esterification plant	potassium sulphate, as K2O, from rape oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	rape methyl ester, at esterification plant	RER	0	kg	9.727E-01	1.00E+02					
product	glycerine, from rape oil, at esterification plant	RER	0	kg	1.061E-01		1.00E+02				
product	potassium sulphate, as K2O, from rape oil, at esterification plant	RER	0	kg	1.64E-02			1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	1.41E-1	1.00E+2	0	0	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	rape oil, at oil mill	RER	0	kg	1.00E+0	8.69E+1	1.29E+1	2.21E-1	1	1.21	(1,2,1,1,1,5); Literature data & biodiesel
	methanol, at plant	GLO	0	kg	1.10E-1	8.69E+1	1.29E+1	2.21E-1	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	4.11E-2	8.69E+1	1.29E+1	2.21E-1	1	1.07	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	8.99E-1	8.69E+1	1.29E+1	2.21E-1	1	1.07	
	transport, freight, rail	RER	0	tkm	7.56E-2	8.69E+1	1.29E+1	2.21E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.26E-2	8.69E+1	1.29E+1	2.21E-1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	8.69E+1	1.29E+1	2.21E-1	1	3.06	(1,4,1,3,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	RER	0	kg	2.66E-2	8.69E+1	1.29E+1	2.21E-1	1	1.56	(5,5,1,2,1,na); Literature,
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	4.48E-3	8.69E+1	1.29E+1	2.21E-1	1	1.09	(2,2,1,2,1,3); Literature data & biodiesel
	potassium hydroxide, at regional storage	RER	0	kg	1.10E-2	8.69E+1	1.29E+1	2.21E-1	1	1.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.08E-5	8.69E+1	1.29E+1	2.21E-1	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.21E-1	0	9.72E+1	2.84E+0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.46E+0	8.69E+1	1.29E+1	2.21E-1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.9 Oil and methyl ester from palm fruit bunches, MY

17.9.1 System characterization

The system described in this paragraph includes (1) the production of palm oil, palm kernel oil and palm kernel meal from palm fruit bunches, and (2) the production of palm methyl ester and glycerine from palm oil, in the Malaysian context (Fig. 17.14).

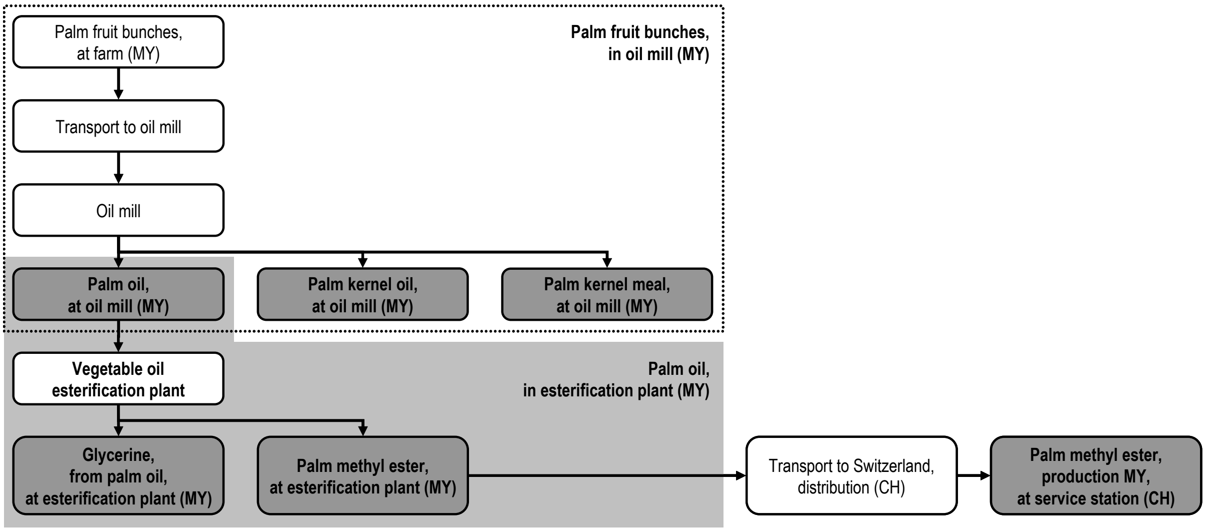


Fig. 17.14 Oil and methyl ester from palm fruit, MY: system definition and boundaries.

If the production of palm oil has always been part of the Malysian culture, it's only recently, with the growing interest and demand for biofuels, that the production of methyl ester from palm oil has been developing on a larger scale in the country. In 2004, one foreign-owned new project was approved for the production of palm methyl ester from palm oil, mainly for the export market. This project would be the first project leading to the production of biodiesel on a commercial scale in Malaysia.

Being the world's first producer of palm oil, Malaysia however offers a significant potential for low-cost palm methyl ester production and is drawing the attention of more and more foreign investors. Even if the production of biodiesel from palm oil remains today marginal, numerous specialists see Malaysia as a potential key player on the scene of international biodiesel commerce in the near future. If the production indeed develops, the technology is very likely to be similar to that in EU countries and the US. The same considerations apply to most developing countries moving towards biodiesel (e.g. Brazil, Indonesia, Thailand, etc.).

The average production of a medium size palm oil mill in Malaysia is 400 tons of palm fruit bunches (PFB) per day (i.e. 150'000 t/yr), which corresponds to 100-150 ha of land, according to average yield in the country (Kittikun 2000).

The process described in this paragraph is based on the current practise for oil extraction (wet milling), and on the technology employed in the EU for the conversion of oil to methyl ester.

Although PFB may be processed through dry milling, wet milling is the most common technique for palm oil extraction in Malaysia, Indonesia and Thailand. The process is well documented in (Hirsinger et al. 1995b) and (Kittikun 2000), and the description given below is based on these two references.

In order to understand the process of palm oil and kernel oil extraction, it is important to describe the structure of palm fruit bunches and define the appropriate vocabulary (Fig. 17.15).

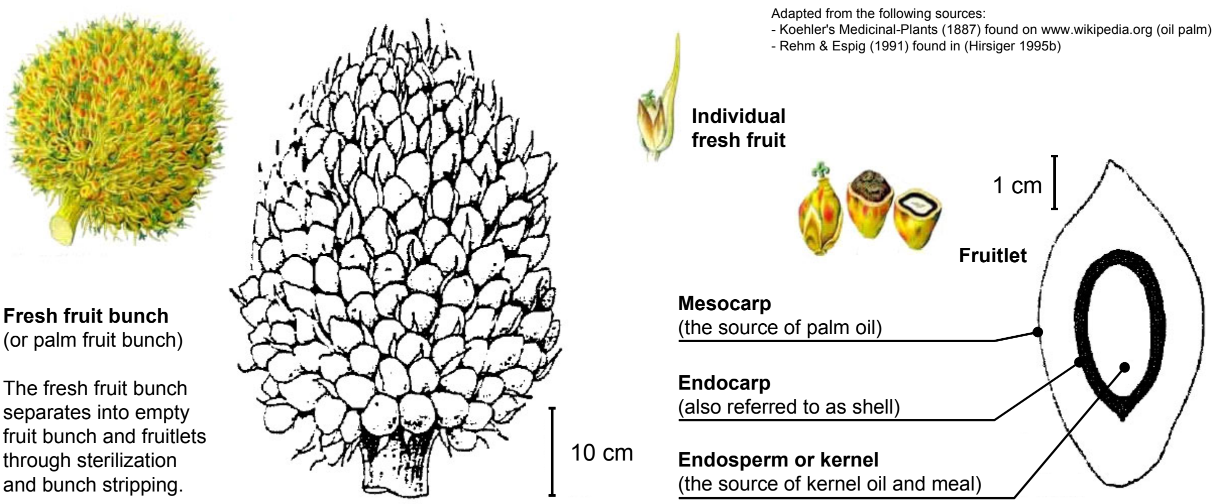


Fig. 17.15 Structure of palm fruit bunches and definition of the vocabulary. (Sources: see references on the image)

Fresh palm fruit bunches consist of the envelope (empty fruit bunch) and individual fruitlets. Fruitlets consist of three main components, namely (1) the mesocarp (i.e. the flesh of the fruit consisting mainly of oil and fibres, and the source of palm oil), (2) the endocarp (more commonly referred to as "shell"), and (3) the endosperm or kernel (the source of palm kernel oil and palm kernel meal). The composition of palm fruit bunches is given in Tab. 17.15.

Tab. 17.15 Composition of palm fruit bunches (Henson 1997).

Palm oil bunch composition / Coastal site			
Components	Percentage (%) of		
	fresh weight	dry weight	energy
Water	48.7%	-	-
Empty fruit bunch	8.9%	17.4%	11.2%
Fruit	42.4%	82.6%	88.8%
Fibres	9.9%	19.3%	12.3%
Oil	23.9%	46.5%	61.6%
Shell	5.0%	9.8%	8.1%
Kernel meal	1.7%	3.3%	2.1%
Kernel oil	1.9%	3.7%	4.7%
Total	100.0%	100.0%	100.0%
Energy content	30.1 MJ/kg DM		

Palm oil bunch composition / Inland site			
Components	Percentage (%) of		
	fresh weight	dry weight	energy
Water	45.8%	-	-
Empty fruit bunch	9.6%	17.7%	11.6%
Fruit	44.6%	82.3%	88.4%
Fibre	9.8%	18.1%	11.8%
Oil	22.5%	41.6%	56.2%
Shell	7.7%	14.2%	12.1%
Fibre	2.1%	3.9%	2.6%
Kernel oil	2.4%	4.5%	5.7%
Total	100.0%	100.0%	100.0%
Energy content	29.5 MJ/kg DM		

The wet milling process is characterized by steaming the whole PFB in order to inactivate the natural enzymes, loosen the fruits off the bunch and soften the mesocarp, resulting in easier extraction of oil.

Soon after harvesting, the PFB must be brought to the mill as quickly as possible to avoid fatty acids production by natural enzymes in the mesocarp. The fruit bunches are first sterilized in an autoclave with the application of steam for approximately 1-2 hours. The steam condensate leaves the sterilizer as wastewater. The sterilised bunches are passed into a rotary drum thresher where the fruits are separated from the bunch. This processing separates the empty fruit bunches from the fruitlets (Fig. 17.16).

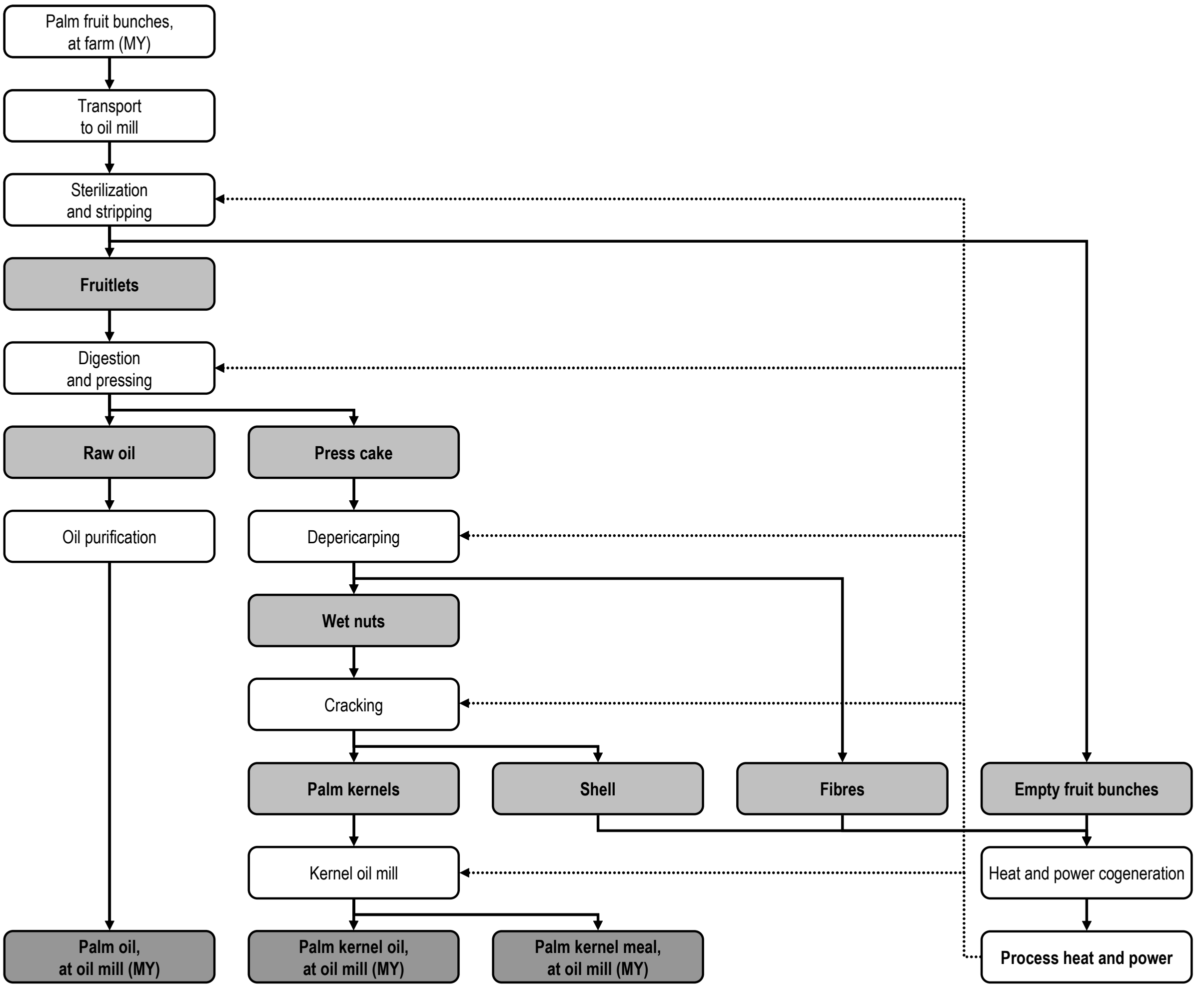


Fig. 17.16 Process stages in a palm oil and palm kernel oil mill (wet milling technique).

The separated fruits are moved into digesters where they are stirred mechanically into an oily mash, which is then fed into a continuous screw press system. The extracted oil phase is collected and is discharged to the purification section. The resulting press cake is transported to a separation system consisting of air classifiers and cyclones in order to dry the material and separate the nuts (consisting of the shell and kernel) and the fibers (so-called depericarping operation). Kernels are then recovered from nuts in a series of crackers. The oil is also extracted from kernels by screw press to obtain palm kernel oil.

The shell, fibres and empty fruit bunches, are used as fuels to power the entire process and supply heat and electricity to the various stages (Fig. 17.16). The whole milling activity is self-sufficient in terms of energy supply.

The oily mash (or raw oil) resulting from the digestion and pressing stages needs to be purified before it can be sold on the market or further processed to palm methyl ester. To improve oil clarification, hot water is added to the raw oil and passed through a vibrating screen to separate large size solids. The oil after sieving still contains small size solids and water. The conventional procedure to separate oil from water and suspended solids is the settling tank method. The system is heated with steam and the oil is extracted at the top of the tank. The underflow is collected in the sludge tank and subsequently treated to recover residual oil. The oil from the settling tank combined with recovered oil from the sludge tank undergoes a final purification by centrifugation to remove fine suspended solids.

After centrifugation the oil still contains water which is removed by means of a vacuum evaporation system. The dried palm oil is kept in storage tanks. Liquid effluents are treated in a local wastewater treatment plant through a system of open ponds.

The smaller-scale extraction of palm kernel oil is assumed to be similar to the (cold-press) extraction of rape oil in the Swiss context and is therefore not described again here. The reader may refer to the description in paragraph 17.6 for further details.

According to the composition palm fruit bunches in Tab. 17.15 and the data in Tab. 17.17, 1 ton of palm fruit bunches (25% oil and 47% water on average) results in:

- 215.8 kg of palm oil;
- 26.6 kg of palm kernel oil;
- 31.7 kg of palm kernel meal.

Allocation between the various products is performed, based on quoted MY market prices (MPOB 2006) of crude palm oil (1’490 RM/t), palm kernel oil (2’565 RM/t) and palm kernel meal (175 RM/t). The resulting allocation factors are indicated in Tab. 17.16.

Tab. 17.16 Allcoation factors for the datasets relating to the production of palm methyl ester (MY).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Oil mill	Palm oil	81.3%	83.1%	78.7%	82.7%
	Palm kernel oil	17.3%	10.3%	9.7%	10.2%
	Palm kernel meal	1.4%	6.6%	11.6%	7.1%
Esterification plant	Rape methyl ester	87.1%	95.0%	90.2%	94.5%
	Glycerine	12.9%	5.0%	9.8%	5.5%

The process of palm oil conversion to methyl esters is considered to be similar to that of rape oil to rape methyl ester. Precipated salts, however, are not considered as an output and are returned to local farmers, as a fertilizer complement. Therefore, the process is not described again here and the reader is advised to refer to paragraph 17.6 for further details.

According to the data in Tab. 17.13, 1 ton of palm oil results in:

- 972.7 kg of palm methyl ester;
- 106.1 kg of glycerine.

Because both products are intended to the European market (MPOB 2006), the same allocation factors as in the EU context are applied. The resulting allocation factors are indicated in Tab. 17.16.

17.9.2 LCI of 'Palm fruit bunches, in oil mill, MY'

The production of palm oil, palm kernel oil and palm kernel meal from palm fruit bunches in the MY context is described in details in paragraph 17.9.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

All material and energy flows in Tab. 17.17 are indicated in reference to 1 ton of palm fruit bunches. The values used in the inventory are given in the last column "ecoinvent". The figures for each input and output are calculated as the average of the data in the shaded boxes. When the data showed significant deviation with the trend of values or when the data was judged incoherent with other values, they were not included in the calculation. Effluents are calculated to close the mass balance.

Tab. 17.17 Literature review of mass and energy balance of palm oil and palm kernel oil extraction.

		Mattson 2000	Yusof & Chan 2004	Ma et al. 2003	Kittikun et al. 2000	Hirsinger et al. 1995b	MPOB 2006	Hoh 2006	Ueno 2001	Schmidt 2004	Calculations	ecoinvent
Oil extraction												
Inputs												
Palm fruit bunches	**kg**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**
Water	kg				605.0						570.0	587.5
Total inputs												1'587.5
Outputs												
Fibres (60% DM)	kg		140.0	139.8	145.0	152.9			150.0		165.0	148.8
Shell (90% DM)	kg		80.0	74.8	60.0	73.6			70.0		59.3	69.6
Empty fruit (40% DM)	kg		230.0	248.7	230.0	228.0			200.0		223.2	226.6
Palm oil	kg	220.0	217.0			217.2	195.7	216.0	220.0	217.4	217.1	215.8
Palm kernel oil	kg	30.0	26.5			29.3	24.1	26.8		26.4	24.1	26.6
Palm kernel meal	kg	36.6				34.8	27.4	30.6		30.5	30.1	31.7
Effluents	kg				893.0						797.1	817.8
Total outputs	kg											1'587.5
Energy in residues (LHV)	MJ		4'973.0	5'024.7	4'653.0	4'982.7					4'651.5	4'849.5
Heat produced	MJ										2'953.7	3'079.5
Electricity produced	kWh										88.4	92.1

Unless stated otherwise, the data below is given per ton of palm fruit bunches.

Palm fruit bunches are transported from palm fields to the mill over an average distance of 100 km, by 16t lorry.

As far as energy is concerned, the respective consumptions of electricity and heat amount to 92.1 kWh and 3'080 MJ per ton of fresh fruit bunches. All the heat and power are produced locally by burning the residues resulting from the extraction of oil (e.g. empty fruit bunches, fibres and shells).

Raw materials used in the process include phosphoric acid (0.194 kg) and hexane (0.672 kg) used as a solvent. The transport distances for the delivery of raw materials include 100 km by 28t lorry and 600 km by train, based on the ecoinvent guidelines.

The consumption of water amounts to 588 kg per ton of fruit bunches. The liquid effluents generated in the process amount to 818 kg and are considered to be treated in a local water treatment plant.

The infrastructure is described in the 'oil mill' dataset (paragraph 17.6.2), with a production capacity of 22'000 t/yr oil, over a lifetime of 50 years. Considering that each ton of fresh fruit bunches yields 242 kg of oil, the infrastructure input per ton of fruit bunches is 2.20E-7 units.

Direct emissions are the result of the combustion of palm residues. Here, the process 'wood chips, burned in cogen 6400kWth' is adapted to the composition of the residues, to model the combustion. The properties of palm residues are given in Tab. 17.18 and compared with wood chips (u=40%).

Tab. 17.18 Characteristics and properties of palm fruit residues, compared with wood chips (u=40%).

	Palm fruit residues		Wood chips, u=40%	
Water content	46.1	% w/w	28.6	% w/w
Dry matter content	53.9	% w/w	71.4	% w/w
Carbon content (dry matter basis)	47.7	% w/w	49.4	% w/w
Higher heating value	19.3	MJ/kg	20.2	MJ/kg
Lower heating value	10.4	MJ/kg	14.4	MJ/kg
Dry matter input	0.539	kg/kg	0.714	kg/kg
Carbon input	0.257	kg/kg	0.353	kg/kg
Energy input	10.375	MJ/kg	14.400	MJ/kg
Heat production	6.588	MJ/kg	11.045	MJ/kg
Electricity production	0.239	kWh/kg	0.331	kWh/kg

The process 'wood chips, burned in cogen 6400kWth' is adapted according to the following rules:

- all inputs from the technosphere are considered to be proportional to the dry matter input;
- emissions of hydrocarbons are proportional to the carbon input (see Tab. 17.18);
- emissions of waste heat are proportional to the energy input (see Tab. 17.18);
- all other emissions are proportional to the dry matter input (see Tab. 17.18).

The three outputs of the MO-process 'palm fruit bunches, in oil mill, MY' include:

- 'palm oil, at oil mill, MY': **215.8 kg/t palm fruit bunches**;
- 'palm kernel oil, at oil mill, MY': **26.6 kg/t palm fruit bunches**;
- 'palm kernel meal, at oil mill, MY': **31.7 kg/t palm fruit bunches**;

The economic allocation approach (paragraph 17.8.2, Tab. 17.16) is used, with allocation factors of 81.3%, 17.3% and 1.4% respectively (applicable to common stages, including the feedstock). The unit process raw data is indicated in Tab. 17.19.

Tab. 17.19 Unit process raw data of the dataset 'palm fruit bunches, in oil mill', MY.

	Name	Location	InfrastructureProcess	Unit	palm fruit bunches, in oil mill	palm oil, at oil mill	palm kernel oil, at oil mill	palm kernel meal, at oil mill	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				MY	MY	MY	MY			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	palm oil, at oil mill	MY	0	kg	2.16E-01	1.00E+02					
product	palm kernel oil, at oil mill	MY	0	kg	2.66E-02		1.00E+02				
product	palm kernel meal, at oil mill	MY	0	kg	3.17E-02			1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	3.56E-2	0	0	1.00E+2	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	palm fruit bunches, at farm	MY	0	kg	1.00E+0	8.13E+1	1.73E+1	1.40E+0	1	1.21	(1,2,1,1,1,5); Literature and industrial data, cross-checking of various references
	transport, freight, rail	RER	0	tkm	5.20E-4	8.13E+1	1.73E+1	1.40E+0	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 16t	RER	0	tkm	1.00E-1	8.13E+1	1.73E+1	1.40E+0	1	2.09	
	transport, lorry 32t	RER	0	tkm	8.66E-5	8.13E+1	1.73E+1	1.40E+0	1	2.09	
	oil mill	CH	1	unit	2.20E-10	8.13E+1	1.73E+1	1.40E+0	1	3.28	(1,4,1,3,4,5); Calculation, according to production capacity and lifetime of the plant
	tap water, at user	RER	0	kg	5.88E-1	8.13E+1	1.73E+1	1.40E+0	1	1.16	(1,3,3,1,1,4); Literature and industrial data
	hexane, at plant	RER	0	kg	6.72E-4	8.13E+1	1.73E+1	1.40E+0	1	1.15	(2,3,1,5,1,3); Literature and industrial data
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	1.94E-4	8.13E+1	1.73E+1	1.40E+0	1	1.10	(2,3,1,2,1,3); Literature data & biodiesel
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	8.18E-4	8.13E+1	1.73E+1	1.40E+0	1	1.16	(1,3,3,1,1,4); Calculation, to close mass balance of process
	ammonia, liquid, at regional storehouse	RER	0	kg	2.95E-8	8.13E+1	1.73E+1	1.40E+0	1	1.32	(4,4,2,1,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (fibres, empty fruit bunch, shell, digester solids)
	chlorine, liquid, production mix, at plant	RER	0	kg	1.18E-6	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	sodium chloride, powder, at plant	RER	0	kg	1.47E-5	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	chemicals organic, at plant	GLO	0	kg	2.06E-5	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	lubricating oil, at plant	RER	0	kg	1.18E-5	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.18E-5	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to landfarming	CH	0	kg	4.75E-4	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	1.18E-5	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	4.75E-4	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	9.53E-4	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	2.83E-6	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	water, decarbonised, at plant	RER	0	kg	2.83E-3	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	cogen unit 6400kWth, wood burning, building	CH	1	unit	8.67E-10	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	cogen unit 6400kWth, wood burning, common components for	CH	1	unit	3.47E-9	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	cogen unit 6400kWth, wood burning, components for electricity only	CH	1	unit	3.47E-9	8.13E+1	1.73E+1	1.40E+0	1	3.10	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	4.63E-1	7.27E+1	2.73E+1	0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	4.64E+0	8.13E+1	1.73E+1	1.40E+0	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Hexane	-	-	kg	6.72E-4	8.13E+1	1.73E+1	1.40E+0	1	1.50	(1,1,1,1,1,1); Calculation, based on hexane input
	Acetaldehyde	-	-	kg	2.19E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	(4,4,2,1,1,5); Adapted from the dataset 'wood chips, in cogen 6400kWth, wood', according to actual water, carbon and energy content of the fuel (fibres, empty fruit bunch, shell, digester solids)
	Ammonia	-	-	kg	6.26E-6	8.13E+1	1.73E+1	1.40E+0	1	1.39	
	Arsenic	-	-	kg	3.60E-9	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Benzene	-	-	kg	3.16E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Benzene, ethyl-	-	-	kg	1.04E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Benzene, hexachloro-	-	-	kg	2.50E-14	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	Benzo(a)pyrene	-	-	kg	1.74E-9	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	Bromine	-	-	kg	2.16E-7	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Cadmium	-	-	kg	2.52E-9	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Calcium	-	-	kg	2.10E-5	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Carbon monoxide, biogenic	-	-	kg	2.43E-5	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Chlorine	-	-	kg	6.47E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Chromium	-	-	kg	1.42E-8	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Chromium VI	-	-	kg	1.44E-10	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Copper	-	-	kg	7.91E-8	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Dinitrogen monoxide	-	-	kg	8.27E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	1.08E-13	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	Fluorine	-	-	kg	1.80E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Formaldehyde	-	-	kg	4.51E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	3.16E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	1.08E-5	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Lead	-	-	kg	8.95E-8	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Magnesium	-	-	kg	1.30E-6	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Manganese	-	-	kg	6.15E-7	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Mercury	-	-	kg	1.08E-9	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Methane, biogenic	-	-	kg	1.51E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	m-Xylene	-	-	kg	4.17E-7	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Nickel	-	-	kg	2.16E-8	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Nitrogen oxides	-	-	kg	3.16E-4	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.12E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	3.82E-8	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	Particulates, < 2.5 um	-	-	kg	1.56E-4	8.13E+1	1.73E+1	1.40E+0	1	3.10	
	Phenol, pentachloro-	-	-	kg	2.81E-11	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Phosphorus	-	-	kg	1.08E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Potassium	-	-	kg	8.41E-5	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Sodium	-	-	kg	4.67E-6	8.13E+1	1.73E+1	1.40E+0	1	5.12	
	Sulfur dioxide	-	-	kg	8.95E-6	8.13E+1	1.73E+1	1.40E+0	1	1.32	
	Toluene	-	-	kg	1.04E-6	8.13E+1	1.73E+1	1.40E+0	1	1.63	
	Zinc	-	-	kg	1.08E-6	8.13E+1	1.73E+1	1.40E+0	1	5.12	

17.9.3 LCI of 'Palm oil, in esterification plant, MY'

The production of methyl ester and glycerine from palm oil in the MY context is described in details in paragraph 17.9.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of palm oil conversion to methyl ester and glycerine is considered to be identical to that of rape oil to methyl ester and glycerine (see paragraph 17.8.3). The yields and allocation factors, however, are specific to the context, and are given below.

The two outputs of the MO-process ‘palm oil, in esterification plant, MY’ include:

- ‘palm methyl ester, at esterification plant, MY’: **972.7 kg/t palm oil**;
- ‘glycerine, from palm oil, at esterification plant, MY’: **106.1 kg/t palm oil**;

The dataset ‘electricity, medium voltage, production NL, at grid’ is used as a proxy for the electricity mix in Malaysia.

The economic allocation approach (paragraph 17.8.2, Tab. 17.16) is used, with allocation factors of 87.1% to methyl ester and 12.9% to glycerine (applicable to common stages, including the feedstock). The corresponding unit process raw data is indicated in Tab. 17.20.

Tab. 17.20 Unit process raw data of the dataset ‘palm oil, in esterifiction plant’, MY.

	Name	Location	InfrastructureProcess	Unit	palm oil, in esterification plant	palm methyl ester, at esterification plant	glycerine, from palm oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				MY	MY	MY			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	palm methyl ester, at esterification plant	MY	0	kg	9.727E-01	1.00E+02				
product	glycerine, from palm oil, at esterification plant	MY	0	kg	1.06E-01		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	2.15E-1	1.00E+2	0	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	palm oil, at oil mill	MY	0	kg	1.00E+0	8.71E+1	1.29E+1	1	1.21	(1,2,1,1,1,5); Literature data & biodiesel producer
	methanol, at plant	GLO	0	kg	1.10E-1	8.71E+1	1.29E+1	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer, NL electricity mix used as a proxy
	electricity, medium voltage, production NL, at grid	UCTE	0	kWh	4.11E-2	8.71E+1	1.29E+1	1	1.07	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	8.99E-1	8.71E+1	1.29E+1	1	1.07	
	transport, freight, rail	RER	0	tkm	7.56E-2	8.71E+1	1.29E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.26E-2	8.71E+1	1.29E+1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	8.71E+1	1.29E+1	1	3.06	(1,4,1,3,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	RER	0	kg	2.66E-2	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Literature, environmental report
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	4.48E-3	8.71E+1	1.29E+1	1	1.09	(2,2,1,2,1,3); Literature data & biodiesel producer
	potassium hydroxide, at regional storage	RER	0	kg	1.10E-2	8.71E+1	1.29E+1	1	1.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.08E-5	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.95E-1	2.71E+1	7.29E+1	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.46E+0	8.71E+1	1.29E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.10 Oil and methyl ester from soybeans, US

17.10.1 System characterization

The system described in this paragraph includes (1) the production of oil and meal from soybeans, and (2) the production of methyl ester and glycerine from soybean oil, in the US context (Fig. 17.17).

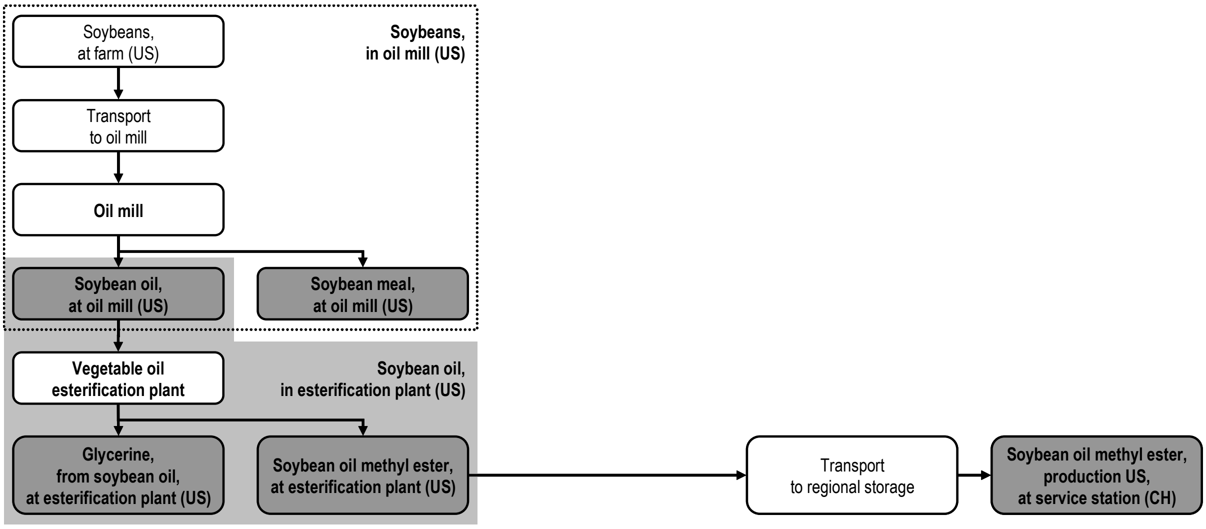


Fig. 17.17 Oil and methyl ester from soybeans, US: system definition and boundaries.

The production of soybean oil is not a straight-forward process. The mechanical extraction of soybean oil with hydraulic presses (cold press technique) is not much used because it's expensive and gives lower yields. Soybean oil is normally produced by solvent extraction. The description of the process is thoroughly document in (Sheehan et al. 1998a) and the description below is based essentially on this study and on the information found in (Soya.be 2006). The data in the present LCI is based on the composition of soybeans as indicated Tab. 17.21, adapted from (Sheehan et al. 1998a).

Tab. 17.21 Composition of soybeans (adapted from Sheehan et al. 1998a).

Average soybeans composition			
Components	Percentage (%) of fresh weight	dry weight	energy
Water	11.0%	-	-
Hulls	7.8%	8.8%	7.1%
Oil	19.5%	21.9%	35.4%
Meal	60.8%	68.3%	57.3%
Other solids	0.8%	1.0%	0.1%
Total	100.0%	100.0%	100.0%
Energy content	23 MJ/kg DM		

The milling process is fairly uniform throughout the US soybean industry and uses solvent extraction to recover the oil, like in the EU context (see paragraph 17.6). The alternative (i.e. mechanical cold-press extraction) represents only 1-2% of the soybeans processed in the US.

Upon arrival at the oil mill, the soybeans are first cleaned, dried and dehulled prior to the extraction of oil. The soybean hulls (or husks, i.e. the leafy outer covering) need to be removed because they absorb oil, resulting in a lower yield. This de-hulling is done through cracking (beans are broken into pieces) and mechanical separation of the hulls and cracked soybeans. After de-hulling, hulls are carried to the meal processing part of the plant. The beans are then conditioned by indirect heating in order to make them more plastic before the beans are cut in flakes (Fig. 17.18).

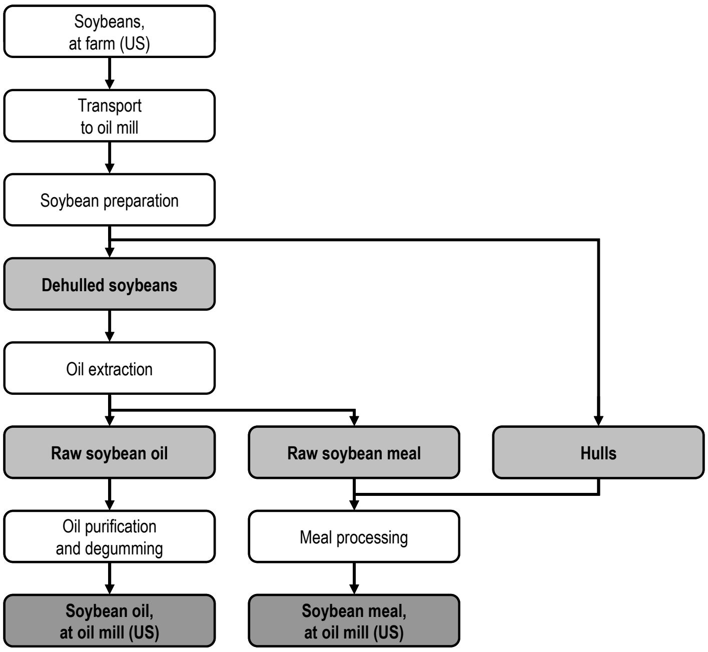


Fig. 17.18 Process stages in a soybean oil mill (solvent extraction technique).

The flakes are then immerged with a solvent, normally hexane. Counterflow extraction is usually used as it gives the highest yield. The extracted flakes contain only about 1% of soybean oil and are used as livestock meal or to produce food products such as soy protein. The hexane is separated from the soybean oil in evaporators. The evaporated hexane is recovered and returned to the extraction process. The hexane free crude soybean oil is then further purified. The rate of solvent addition is assumed to be 1.2 kg of solvent for every kg of flaked beans (i.e. 1.0 kg/kg of fresh beans). Most of this solvent is recovered and recycled, so that the actual hexane make-up usage is only 0.0024 kg/kg of flaked beans (i.e. 0.002 kg/kg of fresh beans).

Further treatment of the meal is required to produce a meal essentially free of hexane and to inactivate enzymes present in the meal. The meal dryer uses indirect steam to reduce moisture content to a level of 12% and hexane to a level of 400 ppm. The meal is then ground and conveyed to final storage and shipment. Hulls are also treated in this part of the plant and are combined with the meal.

The crude soybean oil still contains many soluble and insoluble impurities which need to be removed. Insoluble solids are removed by filtration, while soluble solids are removed by various processes including degumming (removal of phosphatides), alkali refining (removal of free fatty acids, colorants, insoluble matter and residual gums) and bleaching (removal of colour and impurities by means of activated earth or activated carbon).

According to the composition of soybeans (see Tab. 17.21) and the data from (United Soybean Board 2002), 1 ton of soybeans (11% water and 19.5% oil) results in:

- 188.1 kg of soybean oil;
- 794.0 kg of soybean meal (including hulls).

Allocation between the two products is performed, based on quoted US market prices (Beer et al. 2001; United Soybean Board 2002) of crude soybean oil (477 US$/t), soybean meal (214 US$/t). For the allocation with respect to the energy content, heating values for soybean oil and meal, soybean methyl ester and glycerine are taken as 37.2, 17, 37.2 and 18 MJ/kg, respectively. The resulting allocation factors are indicated in Tab. 17.22.

Tab. 17.22 Allcoation factors for the datasets relating to the production of soybean methyl ester (US).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Oil mill	Soybean oil	34.5%	34.1%	19.1%	29.0%
	Soybean meal	65.5%	65.9%	80.9%	71.0%
Esterification plant	Soybean methyl ester	92.0%	95.0%	90.2%	94.5%
	Glycerine	8.0%	5.0%	9.8%	5.5%

The production of soybean methyl ester is considered to be identical to that in the European context in terms of the technology employed. Precipated salts, however, are not considered as an output and are returned to local farmers, as a fertilizer complement. Therefore, the process is not described again here and the reader is advised to refer to paragraph 17.6 for further details.

According to the data in Tab. 17.13, 1 ton of soybean oil results in:

- 972.7 kg of soybean methyl ester;
- 106.1 kg of glycerine.

Allocation between the two products is performed, based on quoted US market prices (Beer et al. 2001; United Soybean Board 2002) of soybean methyl ester (833 US$/t), glycerine (660 US$/t). The resulting allocation factors are indicated in Tab. 17.22.

17.10.2 LCI of 'Soybeans, in oil mill, US'

The production of oil and meal from soybeans in the US context is described in details in paragraph 17.10.1. The present paragraph describes the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

All material and energy flows in Tab. 17.23 are indicated in reference to 1 ton of soybeans. The values used in the inventory are given in the last column "ecoinvent". The figures for each input and output are calculated as the average of the data in the shaded boxes. When the data showed significant deviation with the trend of values or when the data was judged incoherent with other values, they were not included in the calculation. Effluents are calculated to close the mass balance.

Tab. 17.23 Literature review of mass and energy balance of soybean oil extraction.

		Sheehan et al. 1998a	Pimentel & Patzek 2005	Tapasvi et al. 2004	Althaus et al. 2004	Delucchi & Lipman 2003	Beer et al. 2001	US Bureau of Census 2002	O'Connor 2004	ecoinvent
Inputs										
Soybeans (11% water)	**kg**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**	**1'000.0**
Hexane	kg	2.1			0.4		2.1		0.2	2.1
Water	kg	85.8								85.8
Electricity	kWh	56.2			46.1		53.5		71.7	56.2
Steam	MJ	978.0			630.4		1'229.0		839.8	978.0
Total inputs	kg	1'087.9	1'000.0	1'000.0	1'000.4	1'000.0	1'002.1	1'000.0	1'000.2	1'087.9
Outputs										
Soybean oil	kg	179.8	190.7	201.8	178.6	199.2	180.1	188.1	199.9	188.1
Soybean meal	kg	805.3	868.8	798.2	821.4	860.3	805.2	794.0	800.1	794.0
Water vapour	kg	13.9								13.9
Hexane	kg	2.1					1.8			2.1
Effluent stream	kg	82.3					16.7			89.8
Total outputs	kg	1'067.5	1'059.5	1'000.0	1'000.0	1'059.5	1'002.1	982.1	1'000.0	1'087.9

In the present case of soybean oil extraction, only one study (i.e. Sheehan et al. 1998a) is considered satisfactory (for the needs of the present work) amongst the various reports and articles analysed. The work presented in (Sheehan et al. 1998a) is based on actual industrial data from an oil mill in the US, and indeed presents a detailed mass and energy balance for each of the process stages in a complete and comprehensive report. The same data is also used in (Beer et al. 2001). Accordingly, the present dataset is based essentially on that study. The data from other references are however indicated for comparison purposes.

Unless stated otherwise, the data below is from (Sheehan et al. 1998a) and given per ton of soybeans at 11% water (soybeans, indeed, are dried prior to their delivery at the oil mill).

Soybeans are delivered to the mill over an average distance of 100 km, by 16t lorry.

As far as energy is concerned, the respective consumptions of electricity and heat amount to 56.2 kWh (of which 33.5 kWh for common processes, 2.7 kWh for oil-only processes and 20.0 kWh for meal-only operations) and 978 MJ (of which 223 MJ common, 165 MJ oil-only and 590 MJ meal-only) per ton of soybeans. The heat supply in this dataset is described according to the respective shares of coal (11.3%), oil (4.4%) and natural gas (84.3%) in the US industry, as indicated in (EIA 2005).

Raw materials used in the process include phosphoric acid (0.169 kg) and hexane (2.140 kg) used as a solvent. The transport distances for the delivery of raw materials include 100 km by 28t lorry and 600 km by train, according to the ecoinvent guidelines.

The consumption of water amounts to 85.8 kg per ton of soybeans. The liquid effluents generated in the process amount to 89.8 kg and are considered to be treated in a local water treatment plant. Vented water vapour emitted to the atmosphere (13.9 kg) is not included in the inventory.

The infrastructure is described in the 'oil mill' dataset (paragraph 17.6.2), with a production capacity of 22'000 t/yr oil, over a lifetime of 50 years. Considering that each ton of soybeans yields 188 kg of oil, the infrastructure input per ton of fruit bunches is 1.71E-7 units.

Carbon dioxide input and emissions (38.6 kg) are considered to satisfy the carbon balance between oil and meal in spite of the economic allocation. Waste heat (3'236 MJ) is calculated according to the consumption of electricity and energy balance over the entire process.

The two outputs of the MO-process ‘soybeans, in oil mill, US’ include:

- ‘soybean oil, at oil mill, US’: **188.1 kg/t soybeans**;
- ‘soybean meal, at oil mill, US’: **794.0 kg/t soybeans**;

The economic allocation approach (paragraph 17.10.1, Tab. 17.22) is used, with allocation factors of 34.5% to soybean oil and 65.5% to soybean meal (applicable to common stages, including the feedstock). The corresponding unit process raw data is given in Tab. 17.24.

Tab. 17.24 Unit process raw data of the dataset ‘soybeans, in oil mill’, US.

	Name	Location	InfrastructureProcess	Unit	soybeans, in oil mill	soybean oil, at oil mill	soybean meal, at oil mill	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				US	US	US			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	soybean oil, at oil mill	US	0	kg	1.88E-1	1.00E+02				
product	soybean meal, at oil mill	US	0	kg	7.94E-1		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	3.85E-2	1.00E+2	0	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
technosphere	soybeans, at farm	US	0	kg	1.00E+0	3.45E+1	6.55E+1	1	1.11	(1,1,1,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	electricity, medium voltage, at grid	US	0	kWh	5.62E-2	2.54E+1	7.46E+1	1	1.17	(2,4,2,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	1.11E-1	2.47E+1	7.53E+1	1	1.17	
	heat, light fuel oil, at industrial furnace 1MW	RER	0	MJ	4.30E-2	2.47E+1	7.53E+1	1	1.17	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	8.24E-1	2.47E+1	7.53E+1	1	1.17	
	transport, freight, rail	RER	0	tkm	1.39E-3	3.45E+1	6.55E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.15E-4	3.45E+1	6.55E+1	1	2.09	
	transport, lorry 16t	RER	0	tkm	1.00E-1	3.45E+1	6.55E+1	1	2.09	
	oil mill	CH	1	unit	1.71E-10	3.45E+1	6.55E+1	1	3.28	(1,4,1,3,4,5); Calculation, according to production capacity and lifetime of the plant
	tap water, at user	RER	0	kg	8.58E-2	3.45E+1	6.55E+1	1	1.17	(2,4,2,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	hexane, at plant	RER	0	kg	2.14E-3	3.45E+1	6.55E+1	1	1.17	
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	1.69E-4	3.45E+1	6.55E+1	1	1.08	(1,2,1,2,1,3); Literature data & biodiesel producers
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	8.98E-5	3.45E+1	6.55E+1	1	1.57	(5,5,2,1,1,na); Calculation to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.86E-2	0	1.00E+2	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
	Heat, waste	-	-	MJ	3.24E+0	3.45E+1	6.55E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Hexane	-	-	kg	2.14E-3	3.45E+1	6.55E+1	1	1.50	(1,1,1,2,1,3); Emissions are taken to be equal to input of gas

17.10.3 LCI of ‘Soybean oil, in esterification plant, US’

The production of methyl ester and glycerine from soybean oil in the US context is described in details in paragraph 17.10.1. This paragraph means to define the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of soybean oil conversion to methyl ester and glycerine is considered to be identical to that of rape oil to methyl ester and glycerine (see paragraph 17.8.3).

The yields, allocation factors (and hence corrective CO_2 emissions), but also heat and power supply (11.3% coal, 4.4% oil and 84.3% gas for heat according to the Energy Information Administration, and US electricity), however, are specific to the US context.

The two outputs of the MO-process ‘soybean oil, in esterification plant, US’ include:

- ‘soybean methyl ester, at esterification plant, US’: **972.7 kg/t soybean oil**;
- ‘glycerine, from soybean oil, at esterification plant, US’: **106.1 kg/t soybean oil**;

The economic allocation approach (paragraph 17.10.1, Tab. 17.22) is used, with allocation factors of 92.0% to methyl ester and 8.0% to glycerine (applicable to common stages, including the feedstock). The corresponding unit process raw data is indicated in Tab. 17.25.

Tab. 17.25 Unit process raw data of the dataset 'soybean oil, in esterifiction plant', US.

	Name	Location	InfrastructureProcess	Unit	soybean oil, in esterification plant	soybean methyl ester, at esterification plant	glycerine, from soybean oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				US	US	US			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	soybean methyl ester, at esterification plant	US	0	kg	9.73E-01	1.00E+02				
product	glycerine, from soybean oil, at esterification plant	US	0	kg	1.06E-01		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	7.40E-2	1.00E+2	0	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	soybean oil, at oil mill	US	0	kg	1.00E+0	9.20E+1	7.95E+0	1	1.21	(1,2,1,2,1,5); Literature data & biodiesel producer
	methanol, at plant	GLO	0	kg	1.10E-1	9.20E+1	7.95E+0	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	electricity, medium voltage, at grid	US	0	kWh	4.11E-2	9.20E+1	7.95E+0	1	1.07	
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	1.02E-1	9.20E+1	7.95E+0	1	1.07	
	heat, light fuel oil, at industrial furnace 1MW	RER	0	MJ	3.95E-2	9.20E+1	7.95E+0	1	1.07	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	7.57E-1	9.20E+1	7.95E+0	1	1.07	
	transport, freight, rail	RER	0	tkm	7.56E-2	9.20E+1	7.95E+0	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.26E-2	9.20E+1	7.95E+0	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	9.20E+1	7.95E+0	1	3.06	(1,4,1,3,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	RER	0	kg	2.66E-2	9.20E+1	7.95E+0	1	1.56	(5,5,1,2,1,na); Literature, environmental
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	4.48E-3	9.20E+1	7.95E+0	1	1.09	(2,2,1,2,1,3); Literature data & biodiesel producer
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	1.10E-2	9.20E+1	7.95E+0	1	1.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.08E-5	9.20E+1	7.95E+0	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	1.54E-1	5.19E+1	4.81E+1	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.46E+0	9.20E+1	7.95E+0	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.11 Oil and methyl ester from soybeans, BR

Like in the case of Malaysia for palm methyl ester, the production of soybean methyl ester in Brazil is today still marginal. The government, however, has recently launched a massive biodiesel promotion programme, and is drawing the attention of more and more investors and providers of the technology. The technology applied in both the oil extraction and the esterification stages is therefore considered to be identical to the one applied in the US. The only difference will actually lie in the agricultural practise, the yields and the nature of energy supply, more specific of the country.

17.11.1 System characterization

The system described in this paragraph includes (1) the production of soybean oil (incl. distribution) and soybean meal from soybeans, and (2) the production of soybean oil methyl ester and glycerine from soybean oil, in the Brazilian context (Fig. 17.19).

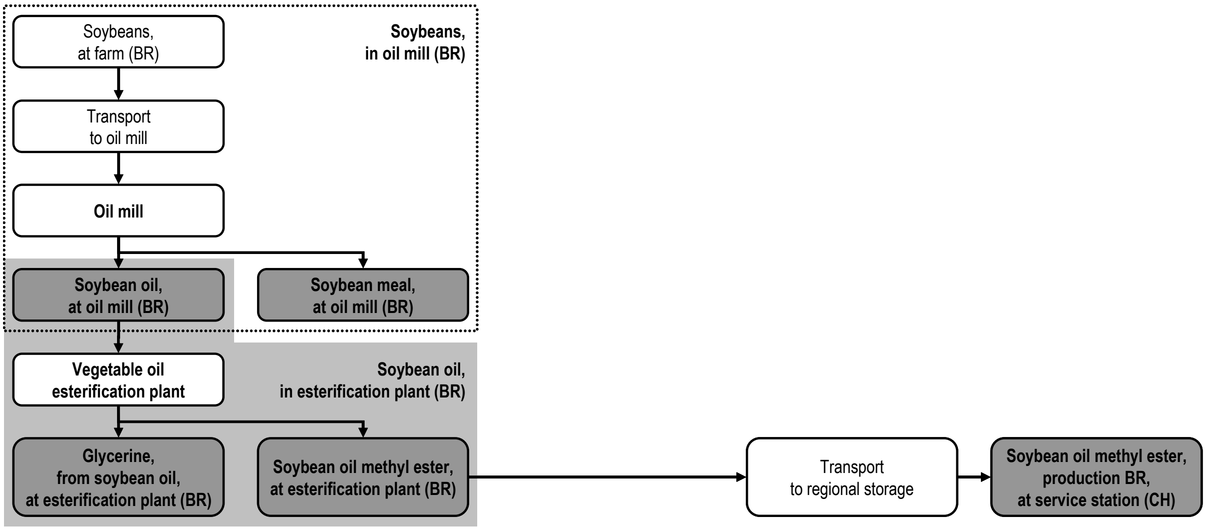


Fig. 17.19 Oil and methyl ester from soybeans, BR: system definition and boundaries.

In 2002, Brazil launched the Probiodiesel Program, as the Directive #702 of the Ministry of Science and Technology (MCT). The program aims to develop technology for the production and use of biodiesel. This biodiesel promotion campaign is translated into the legislation as a mandate to include 2% biodiesel to every litre of diesel fuel starting in 2008, and 5% by 2013. The government is also giving biodiesel producers a reduction on the diesel fuel tax.

In just 12 months, the Government organized the production chain, established lines of credit, structured the technological base and issued a regulatory framework for biodiesel. The commercial use of biodiesel is expected to drive further technological development, thereby speeding up the learning curve and strengthening producers of related goods and services.

The choice of soybean oil as the main feedstock is due to its abundance in Brazil, particularly in the south. With a production of 50 million tons per year (Fig. 17.3) and a milling capacity exceeding 160 kt per day over 12 different states, Brazil is indeed the second largest producer of soybeans in the world.

The technology for the extraction of oil from soybeans is considered to be identical to that in the US context. Therefore, the process is not described again here and the reader should refer to paragraph 17.10.1 for further details. The yields of oil and meal, however, are adapted to the Brazilian context.

According to the composition of soybeans (see Tab. 17.21) and the data from (USMEF 2003), 1 ton of soybeans (11% water and 19.5% oil) results in:

- 182.4 kg of soybean oil;
- 758.2 kg of soybean meal (incl. hulls).

Allocation between the two products is based on quoted BR market prices (USMEF 2003) of soybean oil (1’272 R$/t) and soybean meal (445 R$/t). The allocation factors are shown in Tab. 17.26.

Tab. 17.26 Allcoation factors for the datasets relating to the production of soybean methyl ester (BR).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Oil mill	Soybean oil	40.7%	34.5%	19.4%	29.3%
	Soybean meal	59.3%	65.5%	80.6%	70.7%
Esterification plant	Soybean methyl ester	92.0%	95.0%	90.2%	94.5%
	Glycerine	8.0%	5.0%	9.8%	5.5%

The production of soybean methyl ester is considered to be identical to that in the European context in terms of the technology employed. Precipated salts, however, are not considered as an output and are returned to local farmers, as a fertilizer complement. Therefore, the process is not described again here and the reader is advised to refer to paragraph 17.6 for further details. Considering that the technology is likely to be imported in Brazil from the US or the EU, the yields of soybean methyl ester and glycerine are considered to be equal to those in the US context.

According to the data in Tab. 17.13, 1 ton of soybean oil results in:

- 972.7 kg of soybean methyl ester;
- 106.1 kg of glycerine.

Due to the absence of data concerning prices of glycerine in Brazil, the economic allocation between the two products is based on the respective price levels in the US (see Tab. 17.26).

17.11.2 LCI of 'Soybeans, in oil mill, BR'

The production of oil and meal from soybeans in the BR context is described in details in paragraph 17.11.1. This paragraph means to define the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of soybean oil extraction is considered to be identical to that in the US. For further details, the reader should refer to paragraph 17.10.2.

The yields, allocation factors (and hence corrective emissions of CO_2), but also heat and power supply (12.7% coal, 5.4% oil and 81.9% gas for heat, and BR electricity), however, are specific to BR.

The two outputs of the MO-process 'soybeans, in oil mill, BR' include:

- 'soybean oil, at oil mill, BR': **182.4 kg/t soybeans**;
- 'soybean meal, at oil mill, BR': **758.2 kg/t soybeans**;

The economic allocation approach (paragraph 17.11.1, Tab. 17.26) is used, with allocation factors of 40.7% to oil and 59.3% to meal (applicable to common stages, including the feedstock). The corresponding unit process raw data is indicated in Tab. 17.27.

Tab. 17.27 Unit process raw data of the dataset 'soybeans, in oil mill', BR.

	Name	Location	InfrastructureProcess	Unit	soybeans, in oil mill	soybean oil, at oil mill	soybean meal, at oil mill	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				BR	BR	BR			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	soybean oil, at oil mill	BR	0	kg	1.82E-1	1.00E+02				
product	soybean meal, at oil mill	BR	0	kg	7.58E-1		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	1.02E-2	0	1.00E+2	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
technosphere	soybeans, at farm	BR	0	kg	1.00E+0	4.07E+1	5.93E+1	1	1.11	(1,1,1,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	electricity, medium voltage, at grid	BR	0	kWh	5.62E-2	2.91E+1	7.09E+1	1	1.17	(2,4,2,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	1.24E-1	2.62E+1	7.38E+1	1	1.17	
	heat, light fuel oil, at industrial furnace 1MW	RER	0	MJ	5.28E-2	2.62E+1	7.38E+1	1	1.17	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	8.01E-1	2.62E+1	7.38E+1	1	1.17	
	transport, freight, rail	RER	0	tkm	1.38E-3	4.07E+1	5.93E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.15E-4	4.07E+1	5.93E+1	1	2.09	
	transport, lorry 16t	RER	0	tkm	1.00E-1	4.07E+1	5.93E+1	1	2.09	
	oil mill	CH	1	unit	1.66E-10	4.07E+1	5.93E+1	1	3.28	(1,4,1,3,4,5); Calculation, according to production capacity and lifetime of the plant
	tap water, at user	RER	0	kg	8.58E-2	4.07E+1	5.93E+1	1	1.17	(2,4,2,1,1,4); Based on US study, cross-checking with various literature references, industrial data
	hexane, at plant	RER	0	kg	2.14E-3	4.07E+1	5.93E+1	1	1.17	
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	1.64E-4	4.07E+1	5.93E+1	1	1.08	(1,2,1,2,1,3); Literature data & biodiesel producers
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	8.98E-5	4.07E+1	5.93E+1	1	1.57	(5,5,2,1,1,na); Calculation to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	6.67E-2	1.00E+2	0	1	1.05	(1,1,1,1,1,na); Correction to close carbon balance of individual outputs
	Heat, waste	-	-	MJ	4.03E+0	4.07E+1	5.93E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
	Hexane	-	-	kg	2.14E-3	4.07E+1	5.93E+1	1	1.50	(1,1,1,2,1,3); Emissions are taken to be equal to input of gas

17.11.3 LCI of 'Soybean oil, in esterification plant, BR'

The production of methyl ester and glycerine from soybean oil in BR context is described in details in paragraph 17.11.1. This paragraph means to define the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of soybean oil conversion to methyl ester and glycerine is considered to be identical to that of rape oil to methyl ester and glycerine (see paragraph 17.8.3).

The yields, allocation factors (and hence corrective CO_2 emissions), but also heat and power supply (12.7% coal, 5.4% oil and 81.9% gas for heat, and BR electricity), however, are specific to BR.

The two outputs of the MO-process ‘soybean oil, in esterification plant, BR’ include:

- ‘soybean methyl ester, at esterification plant, BR’: **972.7 kg/t soybean oil**;
- ‘glycerine, from soybean oil, at esterification plant, BR’: **106.1 kg/t soybean oil**;

The economic allocation approach (paragraph 17.11.1, Tab. 17.26) is used, with allocation factors of 92.0% to methyl ester and 8.0% to glycerine (applicable to common stages, including the feedstock). The corresponding unit process raw data is indicated in Tab. 17.28.

Tab. 17.28 Unit process raw data of the dataset ‘soybean oil, in esterification plant’, BR.

	Name	Location	InfrastructureProcess	Unit	soybean oil, in esterification plant	soybean methyl ester, at esterification plant	glycerine, from soybean oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				BR	BR	BR			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	soybean methyl ester, at esterification plant	BR	0	kg	9.73E-01	1.00E+02				
product	glycerine, from soybean oil, at esterification plant	BR	0	kg	1.06E-01		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	7.40E-2	1.00E+2	0	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	soybean oil, at oil mill	BR	0	kg	1.00E+0	9.20E+1	7.96E+0	1	1.21	(1,2,1,2,1,5); Literature data & biodiesel producer
	methanol, at plant	GLO	0	kg	1.10E-1	9.20E+1	7.96E+0	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	electricity, medium voltage, at grid	BR	0	kWh	4.11E-2	9.20E+1	7.96E+0	1	1.07	
	heat, at hard coal industrial furnace 1-10MW	RER	0	MJ	1.14E-1	9.20E+1	7.96E+0	1	1.07	
	heat, light fuel oil, at industrial furnace 1MW	RER	0	MJ	4.85E-2	9.20E+1	7.96E+0	1	1.07	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	7.36E-1	9.20E+1	7.96E+0	1	1.07	
	transport, freight, rail	RER	0	tkm	7.56E-2	9.20E+1	7.96E+0	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.26E-2	9.20E+1	7.96E+0	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	9.20E+1	7.96E+0	1	3.06	(1,4,1,3,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	RER	0	kg	2.66E-2	9.20E+1	7.96E+0	1	1.56	(5,5,1,2,1,na); Literature, environmental report
	hydrochloric acid, 30% in H2O, at plant	RER	0	kg	4.48E-3	9.20E+1	7.96E+0	1	1.09	(2,2,1,2,1,3); Literature data & biodiesel producer
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	1.10E-2	9.20E+1	7.96E+0	1	1.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.08E-5	9.20E+1	7.96E+0	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	1.54E-1	5.19E+1	4.81E+1	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.46E+0	9.20E+1	7.96E+0	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.12 Vegetable oil from waste cooking oil, CH

17.12.1 System characterization

The system described in this paragraph includes the production of vegetable oil from waste cooking oil, in the Swiss context (Fig. 17.20). The process and technology are described in detail in paragraph 17.5.2, which the reader should refer to for further details. The LCI data is given in paragraph 17.12.2.

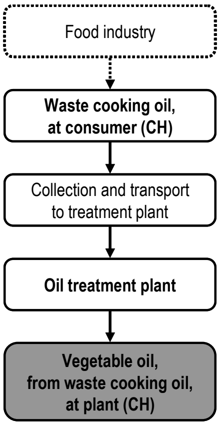


Fig. 17.20 Vegetable oil from waste cooking oil, CH: system definition and boundaries.

17.12.2 LCI of 'Vegetable oil, from waste cooking oil, at plant, CH'

The unit process 'vegetable oil, from waste cooking oil, at plant' envisages the treatment of waste cooking vegetable oil for use in the production of biodiesel. As mentioned before (see section 17.6), the waste oil refining process aims at removing all impurities as well as water from the waste oil in order to conform to the standards for subsequent methyl ester production.

This process includes the collection of waste vegetable oil and delivery to the treatment plant, treatment for impurities and water removal, conditioning and storage of the oil. Treatment of effluents is taken into account as well as the carbon dioxide credit. System boundary is at the oil refining facility.

The waste oil, prior to its collection and refining, is considered here to have no value and is attributed a zero impact. The gross calorific value of the biomass is not included, as it has been accounted for in the first place for the primary use of the vegetable oil. The carbon dioxide credit (i.e. 2.84 kg CO_2/kg), however, is taken into account according to the composition of the treated vegetable oil (see Tab. 16.4).

The process of waste cooking oil refining mainly consists in the esterification of the free fatty acids (6.5% wt.) contained in the waste oil and the technology is indeed very similar to the transesterification of vegetable oil into methyl ester. Due to a significant lack of data (very few extensive studies actually deal with the subject), the refining process is therefore apparented to the esterification process as far as energy use and infrastructure are concerned.

The present process is considered to be acid-catalyzed, based on (Zhang 2003a) which indicates the consumption of methanol (26.9 kg/t of purified oil), glycerine (105.6 kg/t of purified oil for washing the water and sulphuric acid away) and sulphuric acid (2.1 kg/t of purified oil). The quantities (141.3 kg/t of purified oil) and density (1'185 kg/m^3) of liquid effluents is based on (Zhang 2003a). Waste treatment is described with standard treatment and quality. Emissions of biogenic oil to the soil are considered to be 0.05%, according to the ecoinvent guidelines. Finally, CO_2 emissions are considered in order to close the carbon balance. These are the result of some of the initial carbon going to the waste stream.

Standard transport distances are considered for delivery of raw materials (600 km by train and 50 km by 28t lorry) and waste oil collection (100 km by 16t lorry).

The refined waste vegetable oil consists of 6.5% (wt.) of FAME and 93.5% (wt.) of triglycerides. The overall percentage weight of fossil carbon in the oil is 0.3% (wt.), corresponding to a 4.1% of fossil carbon in the 6.5% of FAME. The remaining carbon in the oil is biogenic carbon.

The unit process raw data of the dataset 'vegetable oil, from waste cooking oil, at plant, CH' is given in Tab. 17.29.

Tab. 17.29 Unit process raw data of the dataset 'vegetable oil, from waste cooking oil, at plant', CH.

	Name	Location	InfrastructureProcess	Unit	vegetable oil, from waste cooking oil, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				kg			
product	vegetable oil, from waste cooking oil, at plant	CH	0	kg	1.00E+0			
resource, in air	Carbon dioxide, in air	-	-	kg	2.84E+0	1	1.30	(1,5,1,1,3,na); Calculated from composition of waste cooking oil
technosphere	electricity, medium voltage, at grid	CH	0	kWh	5.08E-2	1	1.62	(4,5,1,2,4,na); Data from transesterification process, considered weak
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	7.73E-1	1	1.62	(4,5,1,2,4,na); Data from transesterification process, from process modelling
	transport, freight, rail	CH	0	tkm	8.08E-2	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	6.73E-3	1	2.09	
	transport, lorry 16t	CH	0	tkm	1.01E-1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	1	3.09	(4,5,1,2,1,na); Oil refining facility modelled as esterification plant
	methanol, at regional storage	CH	0	kg	2.69E-2	1	1.60	(4,4,1,2,4,4); Model data from one literature source
	glycerine, from rape oil, at esterification plant	CH	0	kg	1.06E-1	1	1.60	
	sulphuric acid, liquid, at plant	RER	0	kg	2.10E-3	1	1.60	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.19E-4	1	2.29	(5,5,1,2,5,4); Adapted from weak data from one literature source
emission air, high population density	Heat, waste	-	-	MJ	2.62E+0	1	1.05	(1,1,1,2,1,na); Calculation
	Carbon dioxide, biogenic	-	-	kg	1.67E-1	1	1.30	(4,5,na,na,na,na); Calculation, to close carbon balance
emission soil, industrial	Oils, biogenic	-	-	kg	5.00E-4	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
emission water, river	BOD5, Biological Oxygen Demand	-	-	kg	3.50E-3	1	1.70	(4,5,2,5,3,4); Calculation, according to emissions of oil to soil
	COD, Chemical Oxygen Demand	-	-	kg	3.50E-3	1	1.70	
	DOC, Dissolved Organic Carbon	-	-	kg	4.33E-4	1	1.70	
	TOC, Total Organic Carbon	-	-	kg	4.33E-4	1	1.70	

17.13 Vegetable oil and methyl ester from waste cooking oil, FR

17.13.1 System characterization

The system described in this paragraph includes (1) the production of vegetable oil from waste cooking oil, and (2) the production of vegetable oil methyl ester and glycerine from vegetable oil, in the French context (Fig. 17.21).

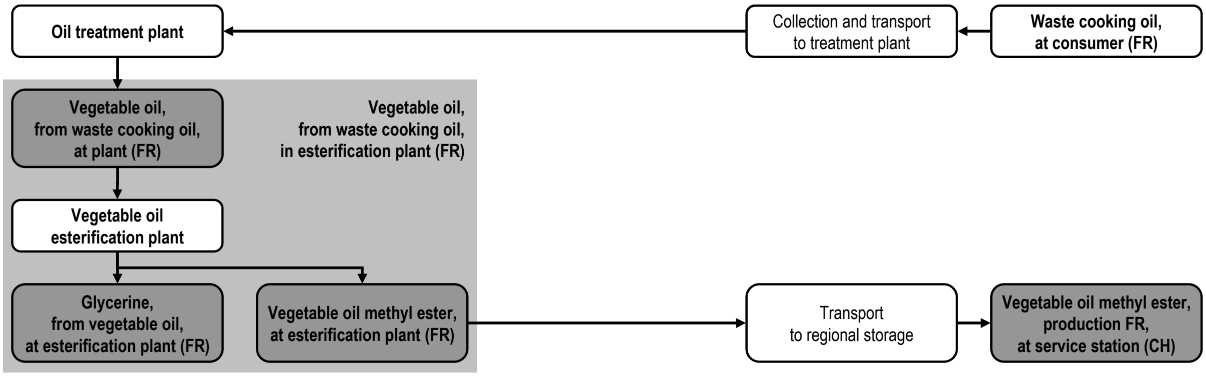


Fig. 17.21 Oil and methyl ester from waste cooking oil, FR: system definition and boundaries.

The process and technology are described in detail in paragraph 17.5.2, which the reader should refer to for further details. The LCI data is given in paragraph 17.13.2.

The conversion of the oil into methyl ester and glycerine is then identical to the production of rape methyl ester. The technology is described in detail in paragraph 17.6.

According to the data in Tab. 17.13, 1 ton of vegetable oil from waste cooking oil results in:

- 972.7 kg of vegetable oil methyl ester;
- 106.1 kg of glycerine.

Allocation between the two products is based on prices quoted in (Schöpe & Britschkat, 2002). The allocation is 87.1% to rape methyl ester and 12.9% to glycerine. The allocation factors for the various methods are indicated in Tab. 17.30.

Tab. 17.30 Allcoation factors for the datasets relating to the production of vegetable oil methyl ester (FR).

Stages	Products	Economic value	Energy content	Mass	Carbon content
Esterification plant	Methyl ester	87.1%	95.0%	90.2%	94.5%
	Glycerine	12.9%	5.0%	9.8%	5.5%

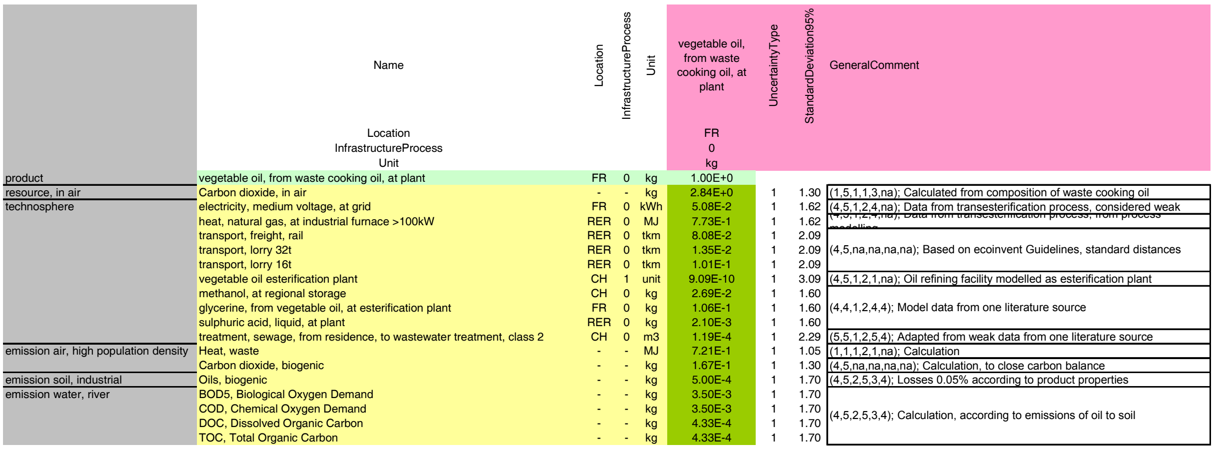
17.13.2 LCI of 'Vegetable oil, from waste cooking oil, at plant, FR'

The production of vegetable oil, from waste cooking oil in the French context is described in details in paragraph 17.13.1. This paragraph means to define the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of waste cooking oil refining is considered to be identical to that in CH. For further details, the reader should refer to paragraph 17.12.2. FR- and/or RER-specific inputs are used whenever it is possible (e.g. transport, methanol, electricity). Heat is considered to be produced from natural gas combustion, like in the Swiss case.

The unit process raw data of the dataset 'vegetable oil, from waste cooking oil, at plant, FR' is given in Tab. 17.31.

Tab. 17.31 Unit process raw data of the dataset 'vegetable oil, from waste cooking oil, at plant', FR.



	Name	Location	InfrastructureProcess	Unit	vegetable oil, from waste cooking oil, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				FR			
	InfrastructureProcess				0			
	Unit				kg			
product	vegetable oil, from waste cooking oil, at plant	FR	0	kg	1.00E+0			
resource, in air	Carbon dioxide, in air	-	-	kg	2.84E+0	1	1.30	(1,5,1,1,3,na); Calculated from composition of waste cooking oil
technosphere	electricity, medium voltage, at grid	FR	0	kWh	5.08E-2	1	1.62	(4,5,1,2,4,na); Data from transesterification process, considered weak
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	7.73E-1	1	1.62	(4,5,1,2,4,na); Data from transesterification process, from process modelling
	transport, freight, rail	RER	0	tkm	8.08E-2	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.35E-2	1	2.09	
	transport, lorry 16t	RER	0	tkm	1.01E-1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	1	3.09	(4,5,1,2,1,na); Oil refining facility modelled as esterification plant
	methanol, at regional storage	CH	0	kg	2.69E-2	1	1.60	(4,4,1,2,4,4); Model data from one literature source
	glycerine, from vegetable oil, at esterification plant	FR	0	kg	1.06E-1	1	1.60	
	sulphuric acid, liquid, at plant	RER	0	kg	2.10E-3	1	1.60	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.19E-4	1	2.29	(5,5,1,2,5,4); Adapted from weak data from one literature source
emission air, high population density	Heat, waste	-	-	MJ	7.21E-1	1	1.05	(1,1,1,2,1,na); Calculation
	Carbon dioxide, biogenic	-	-	kg	1.67E-1	1	1.30	(4,5,na,na,na,na); Calculation, to close carbon balance
emission soil, industrial	Oils, biogenic	-	-	kg	5.00E-4	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
emission water, river	BOD5, Biological Oxygen Demand	-	-	kg	3.50E-3	1	1.70	(4,5,2,5,3,4); Calculation, according to emissions of oil to soil
	COD, Chemical Oxygen Demand	-	-	kg	3.50E-3	1	1.70	
	DOC, Dissolved Organic Carbon	-	-	kg	4.33E-4	1	1.70	
	TOC, Total Organic Carbon	-	-	kg	4.33E-4	1	1.70	

17.13.3 Vegetable oil, from waste cooking oil, in esterification plant, FR

The production of methyl ester and glycerine from vegetable oil in FR context is described in details in paragraph 17.13.1. This paragraph means to define the actual life cycle inventory (LCI) of the process as defined in the ecoinvent database.

The life cycle inventory of vegetable oil conversion to methyl ester and glycerine is considered to be identical to that of rape oil to methyl ester and glycerine. For further details, the reader should refer to paragraph 17.8.3.

The two outputs of the MO-process ‘vegetable oil, in esterification plant, FR’ include:

- ‘vegetable oil methyl ester, at esterification plant, FR’: **972.7 kg/t vegetable oil**;
- ‘glycerine, from vegetable oil, at esterification plant, FR’: **106.1 kg/t vegetable oil**;

The economic allocation approach (paragraph 17.11.2, Tab. 17.30) is used, with allocation factors of 87.1% to methyl ester and 12.9% to glycerine (applicable to common stages, including the feedstock). The corresponding unit process raw data is indicated in Tab. 17.32.

Tab. 17.32 Unit process raw data of the dataset ‘vegetable oil, from waste cooking oil, in esterification plant’, FR.

	Name	Location	InfrastructureProcess	Unit	vegetable oil, from waste cooking oil, in esterification plant	vegetable oil methyl ester, at esterification plant	glycerine, from vegetable oil, at esterification plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				FR	FR	FR			
	InfrastructureProcess				0	0	0			
	Unit				kg	kg	kg			
product	vegetable oil methyl ester, at esterification plant	FR	0	kg	9.73E-01	1.00E+02				
product	glycerine, from vegetable oil, at esterification plant	FR	0	kg	1.06E-01		1.00E+02			
resource, in air	Carbon dioxide, in air	-	-	kg	1.36E-1	1.00E+2	0	1	1.07	(1,1,1,2,1,3); Calculation, to close carbon balance
technosphere	vegetable oil, from waste cooking oil, at plant	FR	0	kg	1.00E+0	8.71E+1	1.29E+1	1	1.21	(1,2,1,1,1,5); Literature data & biodiesel producer
	methanol, at plant	GLO	0	kg	1.10E-1	8.71E+1	1.29E+1	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	electricity, medium voltage, at grid	FR	0	kWh	4.11E-2	8.71E+1	1.29E+1	1	1.07	
	heat, natural gas, at industrial furnace >100kW	RER	0	MJ	8.99E-1	8.71E+1	1.29E+1	1	1.07	
	transport, freight, rail	RER	0	tkm	7.56E-2	8.71E+1	1.29E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 32t	RER	0	tkm	1.15E-2	8.71E+1	1.29E+1	1	2.09	
	vegetable oil esterification plant	CH	1	unit	9.09E-10	8.71E+1	1.29E+1	1	3.05	(1,2,1,1,1,5); Calculation, according to feed capacity and lifetime of the plant
	tap water, at user	RER	0	kg	2.66E-2	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Literature, environmental report
	phosphoric acid, industrial grade, 85% in H2O, at plant	RER	0	kg	4.48E-3	8.71E+1	1.29E+1	1	1.07	(1,1,1,2,1,3); Literature data & biodiesel producer
	potassium hydroxide, at regional storage	RER	0	kg	1.10E-2	8.71E+1	1.29E+1	1	1.07	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.08E-5	8.71E+1	1.29E+1	1	1.56	(5,5,1,2,1,na); Calculation, to close mass balance of process
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.15E-1	0	1.00E+2	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	1.42E+1	8.71E+1	1.29E+1	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance

17.14 Distribution of oil-based biofuels

The systems described in this paragraph include:

- the distribution in Switzerland of rape oil and methyl ester produced in Switzerland;
- the distribution in Switzerland of imported methyl ester.

The transport distances involved in the various datasets are summarized in Tab. 16.35.

Tab. 17.33 Summary of the tranport distances involved in the distribution of oil-based biofuels.

Dataset	palm methyl ester, production MY, at service station	vegetable oil methyl ester, production FR, at service station	rape methyl ester, production RER, at service station	soybean methyl ester, production US, at service station	soybean methyl ester, production BR, at service station
Production country/region	MY	FR	RER	US	BR
Transport within producing country/region					
Train				1'400	500
Lorry 32t	100			100	150
Transport overseas	11'700			7'000	10'000
Transport within the EU to Swiss border					
Train	500	600	650		
Lorry 32t		50	150		
Barge				840	840
Transport within Switzerland					
Train	100	100	100	100	100
Lorry 28t	150	150	150	150	150
Total distance	**12'550**	**900**	**1'050**	**9'590**	**11'740**

For reasons of consistency with other datasets relating to the distribution of fuels (e.g. gasoline, diesel), the datasets described in this paragraph are based on the existing dataset 'petrol, unleaded, at regional storage' (Jungbluth 2004). Operation of storage tanks and petrol stations are taken into account. Emissions from the treatment of effluents are included. Fugitive emissions are adapted to the specific nature of methyl ester. Emissions from car-washing at petrol stations however are excluded.

Due to a lack of information about actual distances, standard distances are used for the distribution from the Swiss border to service stations (see Part I of this report). These include 100 km by train and 150 km by 28t lorry.

17.14.1 LCI of 'Rape oil, at regional storage, CH'

The unit process 'rape oil, at regional storage' envisages the transport of rape oil from the oil mill to a regional service station (incl. storage, treatment of effluents) and distribution to the end-user. The unit process raw data of 'rape oil, at regional storage' is indicated in Tab. 17.34.

17.14.2 LCI of 'Rape methyl ester, at regional storage, CH'

The unit process 'rape methyl ester, at regional storage' envisages the transport of rape methyl ester from the esterification plant to a regional service station (incl. storage, treatment of effluents) and distribution to the end-user. The unit process raw data of 'rape methyl ester, at regional storage, CH' is indicated in Tab. 17.34.

Tab. 17.34 Unit process raw data of the datasets relating to the distribution of rape oil and methyl ester, CH.

	Name	Location	InfrastructureProcess	Unit	rape oil, at regional storage	rape methyl ester, at regional storage	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH			
	InfrastructureProcess				0	0			
	Unit				kg	kg			
product	rape oil, at regional storage	CH	0	kg	1.00E+00				
product	rape methyl ester, at regional storage	CH	0	kg		1.00E+00			
technosphere	rape oil, at oil mill	CH	0	kg	1.00E+0		1	1.05	(1,1,1,1,1,1); Product plus losses
	rape methyl ester, at esterification plant	CH	0	kg		1.00E+0	1	1.05	
	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	6.70E-3	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage and filling station)
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	6.21E-4	1	1.25	
	transport, freight, rail	CH	0	tkm	1.00E-1	1.00E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.50E-1	1.50E-1	1	2.09	
	regional distribution, oil products	RER	1	unit	2.62E-10	2.62E-10	1	3.06	(3,na,1,3,3,na); Average data for petrol station
	tap water, at user	CH	0	kg	6.89E-4	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for petrol distribution
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1.68E-4	1	1.27	(2,4,3,3,3,3); Sludge from storage, environmental report and literature
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	6.27E-6	1	1.25	(2,4,1,3,3,3); Environmental report for wastes
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	7.50E-5	1	1.40	(4,5,3,3,3,na); Treatment of rainwater with pollutants
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	6.89E-7	1	1.25	(2,4,1,3,3,3); Used water
emission air, high population density	Heat, waste	-	-	MJ	2.41E-2	2.41E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
emission soil, industrial	Oils, biogenic	-	-	kg	5.00E-4	5.00E-4	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product
emission water, river	BOD5, Biological Oxygen Demand	-	-	kg	3.50E-3	3.50E-3	1	1.70	(4,5,2,5,3,4); Calculation, according to emissions of oil to soil
	COD, Chemical Oxygen Demand	-	-	kg	3.50E-3	3.50E-3	1	1.70	
	DOC, Dissolved Organic Carbon	-	-	kg	4.33E-4	4.33E-4	1	1.70	
	TOC, Total Organic Carbon	-	-	kg	4.33E-4	4.33E-4	1	1.70	

17.14.3 LCI of 'Rape methyl ester, production RER, at service station, CH'

The unit process 'rape methyl ester, production RER, at service station' envisages the import of rape methyl ester from the EU, and the distribution to the end-user at service stations in CH.

Rape methyl ester is produced from rape in the EU context, and is delivered to Geneva or Basel. The distance from the production site to the Swiss border is considered to be 650 km by rail and 150 km by 32t lorry (according to the geographic situation of biodiesel production plants in the EU).

The unit process raw data of the dataset 'rape methyl ester, production RER, at service station, CH' is given in Tab. 17.35.

17.14.4 LCI of 'Palm methyl ester, production MY, at service station, CH'

The unit process 'palm methyl ester, production MY, at service station' envisages the import of palm methyl ester from Malaysia (MY), and distribution to the end-user at service stations in CH.

Palm methyl ester is produced from soybeans in MY. The fuel is transported to a harbour (100 km road) and then overseas to Marseille harbour by tanker (11'700 km via the Suez Canal). Upon arrival in the European Union, it is loaded on trains and delivered to the Swiss border in Geneva (500 km).

The unit process raw data of the dataset 'palm methyl ester, production MY, at service station, CH' is given in Tab. 17.35.

17.14.5 Soybean methyl ester, production US, at service station, CH

The unit process 'soybean methyl ester, production US, at service station' envisages the import of soybean methyl ester from the United States, and distribution to the end-user at service stations in CH.

Soybean methyl ester is produced in the US. It is transported from the esterification plant to a harbour on the East Coast (1'400 km by rail and 100 km road, see Fig. 17.22) and then overseas to Rotterdam harbour by tanker (7'000 km). Upon arrival in the European Union, it is loaded on barges and delivered to the Swiss border in Basel (840 km).

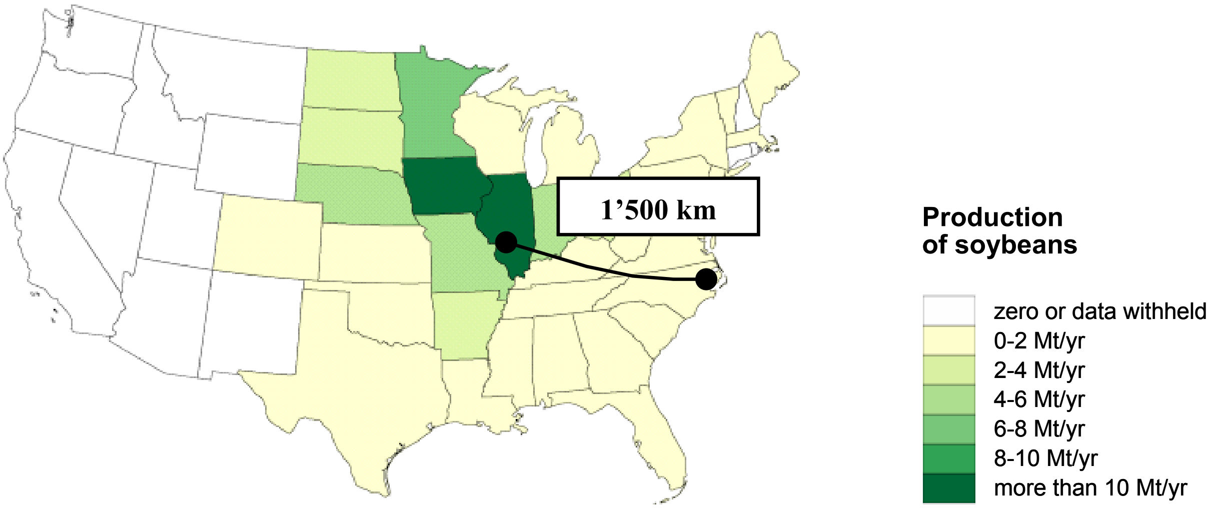


Fig. 17.22 Location of soybean producing States in the US (adapted from USDA NASS, 2006).

The unit process raw data of the dataset 'soybean methyl ester, production US, at service station, CH' is given in Tab. 17.35.

17.14.6 Soybean methyl ester, production BR, at service station, CH

The unit process 'soybean methyl ester, production BR, at service station' envisages the import of soybean methyl ester from Brazil, and distribution to the end-user at service stations in CH.

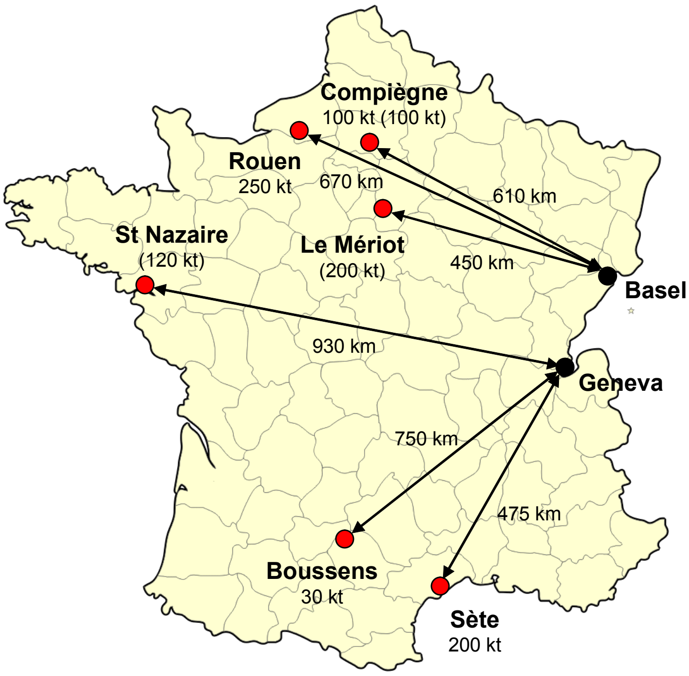
Soybean methyl ester is produced in BR. It is transported from the esterification plant (in the region of São Paulo, where soybean fields are largely concentrated) to a harbour on the East Coast (500 km by rail and 150 km road, see Fig. 17.22) and then overseas to Rotterdam harbour by tanker (10'000 km). Upon arrival in the European Union, it is loaded on barges and delivered to the Swiss border in Basel (840 km).

The unit process raw data of the dataset 'soybean methyl ester, production BR, at service station, CH' is given in Tab. 17.35.

17.14.7 Vegetable oil methyl ester, production FR, at regional storage, CH

The unit process 'vegetable oil methyl ester, production FR, at service station' envisages the import of vegetable oil methyl ester from France, and the distribution to the end-user at service stations in CH.

Vegetable oil methyl ester is produced in FR and is then transported from the esterification plant to the Swiss border in Basel or Geneva (600 km by rail and 50 km road). The average distance is calculated as the distance from the production plants in France weighted according to the respective production capacities (see Fig. 17.23).



Distances are indicated as straight lines although they may not be as such.

Data in kt represent the current production capacity.

Data in brackets indicate the production capacities planned or in construction.

Fig. 17.23 Location of esterification plants in FR (adapted from Partenaires Diester, 2005).

The unit process raw data of the dataset ‘soybean methyl ester, production BR, at service station, CH' is given in Tab. 17.35.

Tab. 17.35 Unit process raw data of the datasets relating to methyl ester imports (CH).

	Name	Location	InfrastructureProcess	Unit	palm methyl ester, production MY, at service station	vegetable oil methyl ester, production FR, at service station	rape methyl ester, production RER, at service station	soybean methyl ester, production US, at service station	soybean methyl ester, production BR, at service station	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0	0			
	Unit				kg	kg	kg	kg	kg			
product	palm methyl ester, production MY, at service station	CH	0	kg	1.00E+00							
product	vegetable oil methyl ester, production FR, at service station	CH	0	kg		1.00E+00						
product	rape methyl ester, production RER, at service station	CH	0	kg			1.00E+00					
product	soybean methyl ester, production US, at service station	CH	0	kg				1.00E+00				
product	soybean methyl ester, production BR, at service station	CH	0	kg					1.00E+00			
technosphere	palm methyl ester, at esterification plant	MY	0	kg	1.00E+0					1	1.05	(1,1,1,1,1,1); Product plus losses
	vegetable oil methyl ester, at esterification plant	FR	0	kg		1.00E+0				1	1.05	
	rape methyl ester, at esterification plant	RER	0	kg			1.00E+0			1	1.05	
	soybean methyl ester, at esterification plant	US	0	kg				1.00E+00		1	1.05	
	soybean methyl ester, at esterification plant	BR	0	kg					1.00E+00	1	1.05	
	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	6.70E-3	6.70E-3	6.70E-3	6.70E-3	1	1.25	(2,4,1,3,3,3); Data for fuel distribution (storage and filling station)
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	6.21E-4	6.21E-4	6.21E-4	6.21E-4	1	1.25	
	transport, freight, rail	RER	0	tkm	5.00E-1	6.00E-1	6.50E-1	1.40E+0	5.00E-1	1	2.09	(4,5,na,na,na,na); Assumption, standard distances
	transport, lorry 32t	RER	0	tkm	1.00E-1	5.00E-2	1.50E-1	1.00E-1	1.50E-1	1	2.09	
	transport, lorry 16t	RER	0	tkm	0	0	0	0	0	1	2.09	
	transport, freight, rail	CH	0	tkm	1.00E-1	1.00E-1	1.00E-1	1.00E-1	1.00E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.50E-1	1.50E-1	1.50E-1	1.50E-1	1.50E-1	1	2.09	
	transport, transoceanic tanker	OCE	0	tkm	1.17E+1	0	0	7.00E+0	1.00E+1	1	2.09	(4,5,na,na,na,na); Assumption, distance to Rotterdam (NL) or Marseille (FR)
	transport, barge tanker	RER	0	tkm	0	0	0	8.40E-1	8.40E-1	1	2.09	(4,5,na,na,na,na); Assumption, Rotterdam to Basel
	regional distribution, oil products	RER	1	unit	2.62E-10	2.62E-10	2.62E-10	2.62E-10	2.62E-10	1	3.06	(3,na,1,3,3,na); Average data for petrol station
	tap water, at user	CH	0	kg	6.89E-4	6.89E-4	6.89E-4	6.89E-4	6.89E-4	1	1.25	(2,4,1,3,3,3); Data for petrol distribution
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1.68E-4	1.68E-4	1.68E-4	1.68E-4	1	1.27	(2,4,3,3,3,3); Sludge from storage, environmental report and
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	6.27E-6	6.27E-6	6.27E-6	6.27E-6	1	1.25	(2,4,1,3,3,3); Environmental report for wastes
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	7.50E-5	7.50E-5	7.50E-5	7.50E-5	1	1.40	(4,5,3,3,3,na); Treatment of rainwater with pollutants
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	6.89E-7	6.89E-7	6.89E-7	6.89E-7	1	1.25	(2,4,1,3,3,3); Used water
emission air, high population density	Heat, waste	-	-	MJ	2.41E-2	2.41E-2	2.41E-2	2.41E-2	2.41E-2	1	1.14	(2,4,1,3,1,3); ecoinvent guidelines, calculation from electricity consumption and energy balance
emission soil, industrial	Oils, biogenic	-	-	kg	5.00E-4	5.00E-4	5.00E-4	5.00E-4	5.00E-4	1	1.70	(4,5,2,5,3,4); Losses 0.05% according to product properties
emission water, river	BOD5, Biological Oxygen Demand	-	-	kg	3.50E-3	3.50E-3	3.50E-3	3.50E-3	3.50E-3	1	1.70	(4,5,2,5,3,4); Calculation, according to emissions of oil to soil
	COD, Chemical Oxygen Demand	-	-	kg	3.50E-3	3.50E-3	3.50E-3	3.50E-3	3.50E-3	1	1.70	
	DOC, Dissolved Organic Carbon	-	-	kg	4.33E-4	4.33E-4	4.33E-4	4.33E-4	4.33E-4	1	1.70	
	TOC, Total Organic Carbon	-	-	kg	4.33E-4	4.33E-4	4.33E-4	4.33E-4	4.33E-4	1	1.70	

17.15 Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation in all the datasets.

17.16 Cumulative Results and Interpretation

17.16.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in (Frischknecht et al. 2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

17.16.2 Selected LCI results and cumulative energy demand

Tab. 16.39 shows selected LCI results (including greenhouse gas emissions) and the cumulative energy demand of vegetable oil methyl ester datasets.

Tab. 17.36 Selected LCI results and the cumulative energy demand of vegetable oil methyl ester datasets.

		Name		rape methyl ester, at esterification plant	rape methyl ester, at esterification plant	palm methyl ester, at esterification plant	soybean methyl ester, at esterification plant	soybean methyl ester, at esterification plant	vegetable oil methyl ester, at esterification plant
		Location		CH	RER	MY	US	BR	FR
		Unit	Unit	kg	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0	0
LCIA results									
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	17.8	22.8	17.0	11.0	31.0	8.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.1	2.8	2.0	1.1	1.3	1.3
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.0	0.7	0.6	0.2	0.3	0.1
	cumulative energy demand	renewable energy resources, wind, solar,	MJ-Eq	0.0	0.1	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	49.4	47.7	54.1	36.8	44.9	0.0
LCI results									
resource	Land occupation	total	m2a	6.2E+0	4.7E+0	1.5E+0	6.8E+0	4.4E+0	7.2E-3
air	Carbon dioxide, fossil	total	kg	8.6E-1	1.2E+0	5.0E-1	5.1E-1	6.0E-1	2.9E-1
air	NMVOC	total	kg	1.2E-3	3.1E-3	8.2E-3	4.4E-3	2.1E-2	3.6E-4
air	Nitrogen oxides	total	kg	6.0E-3	6.3E-3	4.0E-3	2.6E-3	5.1E-3	6.5E-4
air	Sulphur dioxide	total	kg	1.7E-3	3.4E-3	1.3E-3	1.6E-3	2.7E-3	5.0E-4
air	Particulates, < 2.5 um	total	kg	5.4E-4	5.6E-4	3.7E-3	2.1E-4	9.3E-3	5.2E-5
water	BOD	total	kg	2.4E-3	2.6E-3	1.3E-3	1.1E-3	1.4E-3	3.9E-3
soil	Cadmium	total	kg	-1.8E-6	9.0E-7	2.9E-8	-3.0E-8	8.6E-7	3.9E-10
Further LCI results									
air	Carbon dioxide, biogenic	total	kg	-2.7E+0	-2.7E+0	-2.6E+0	-2.7E+0	-2.7E+0	-2.7E+0
air	Carbon dioxide, land transformation	low population density	kg	2.9E-5	1.7E-4	8.3E-1	7.0E-5	2.2E+0	1.8E-5
air	Methane, biogenic	total	kg	3.7E-6	6.5E-6	1.0E-5	2.8E-6	3.6E-6	1.0E-6
air	Carbon monoxide, biogenic	total	kg	8.6E-5	5.1E-5	9.9E-5	2.6E-5	3.4E-5	5.0E-6
	biogenic C-content in product	calculated	kg	0.732	0.734	0.713	0.727	0.726	0.728
	CO2, biogenic-content in product	calculated	kg	2.684	2.691	2.615	2.665	2.663	2.669
	C-content in product	according to product properties -->	kg	0.732	0.732	0.715	0.731	0.731	0.732

The main results of this quoted in Tab. 16.39, more particularly the cumulative energy demand as well as greenhouse gas (GHG) emissions of vegetable oil methyl esters (at esterification plant) are compared with literature data.

In the literature, the cumulative energy demand (CED) is often expressed as the so-called "energy ratio", i.e. the ratio of the energy produced in the form of biofuel to the equivalent non renewable primary energy consumed (i.e. energy out/energy in). This energy ratio is therefore equal to the ratio of the higher heating value (HHV) to the non renewable CED.

The cumulative energy demand (CED) is here limited to non renewable energy (i.e. fossil and nuclear). The "energy ratio" is calculated as the HHV of methyl ester (40.5 MJ/kg) to the CED (in MJ/kg). As far as literature data is concerned, it is often difficult to know whether GHG emissions only include CO_2 or all of GHG according to IPCC, and were therefore quoted as CO_2 emissions arbitrarily.

The comparison is presented in Tab. 16.40.

Tab. 17.37 Comparison of cumulative (non renewable) energy demand and CO_2 emissions of methyl esters (as described in this study) with literature data.

Literature reference	Year	Feedstock of methyl esters	Country	E_{out}/E_{in} MJ/MJ	CED MJ/kg	IPCC 100a kg/kg	CO_2 kg/kg
(Cabela 1982)	1982	Rape	A	2.70	15.0		
(ETSU 1992)	1992	Rape	DE	3.03	13.4		
(Levy 1993)	1993	Rape		1.83	22.1		
(AFAS 1993)	1993	Rape	DE	2.13	19.0		1.46
(VITO 1996)	1996	Rape	BE	1.82	22.3		
(ETSU 1996)	1996	Rape	UK	1.32	30.7		1.30
(ALTENER 1996)	1996	Rape	RER	1.82	22.3		
(IFEU 1997)	1997	Rape	DE	2.56	15.8		1.22
(BLT 1999)	1999	Rape	A	2.70	15.0		
(Levington 2000)	2000	Rape	RER	1.84	22.1		0.57
(BABFO 2000)	2000	Rape	UK	1.79	22.7		
(UFOP 2001)	2001	Rape	DE	2.40	16.9		
(UFOP 2002)	2002	Rape	DE	1.61	25.1		1.29
(GM 2002)	2002	Rape		3.03	13.4		1.10
(CSIRO 2002)	2002	Rape	AUS	2.33	17.4		
(ADEME 2002)	2002	Rape	FR	2.94	13.8		0.76
(Mortimer 2003)	2003	Rape	UK	2.27	17.8		1.01
(Delucchi 2003)	2003	Rape		2.12	19.1		
(Elsayed 2003)	2003	Rape	UK	2.29	17.7		
This study	2006	Rape	CH	1.93	20.9	1.90	0.86
This study	2006	Rape	RER	1.58	25.7	2.59	1.18
(ISLR 1995)	1995	Soybeans	US	2.50	16.2		
(USDA 1998)	1998	Soybeans	US	3.20	12.7		
This study	2006	Soybeans	US	3.34	12.1	1.25	0.51
This study	2006	Soybeans	BR	1.25	32.3	3.86	0.60
This study	2006	Palm	MY	2.13	19.0	1.72	0.50
(Elsayed 2003)	2003	Waste vegetable oil	UK	5.32	7.6		
This study	2006	Waste vegetable oil	FR	4.08	9.9	0.32	0.29

In Tab. 16.40, the impact according to IPCC 100a does not include CO_2 emissions from land transformation (see Tab. 16.39). It is worth noting that, depending on the datasets, the impact may change significantly when taking these emissions into account, especially when the agricultural phase is associated with deforestation (e.g. palm fruit bunches in MY or soybeans in BR).

The data presented in Tab. 16.40 are illustrated in Fig. 16.21 (CED) and Fig. 16.22 (CO_2 emissions).

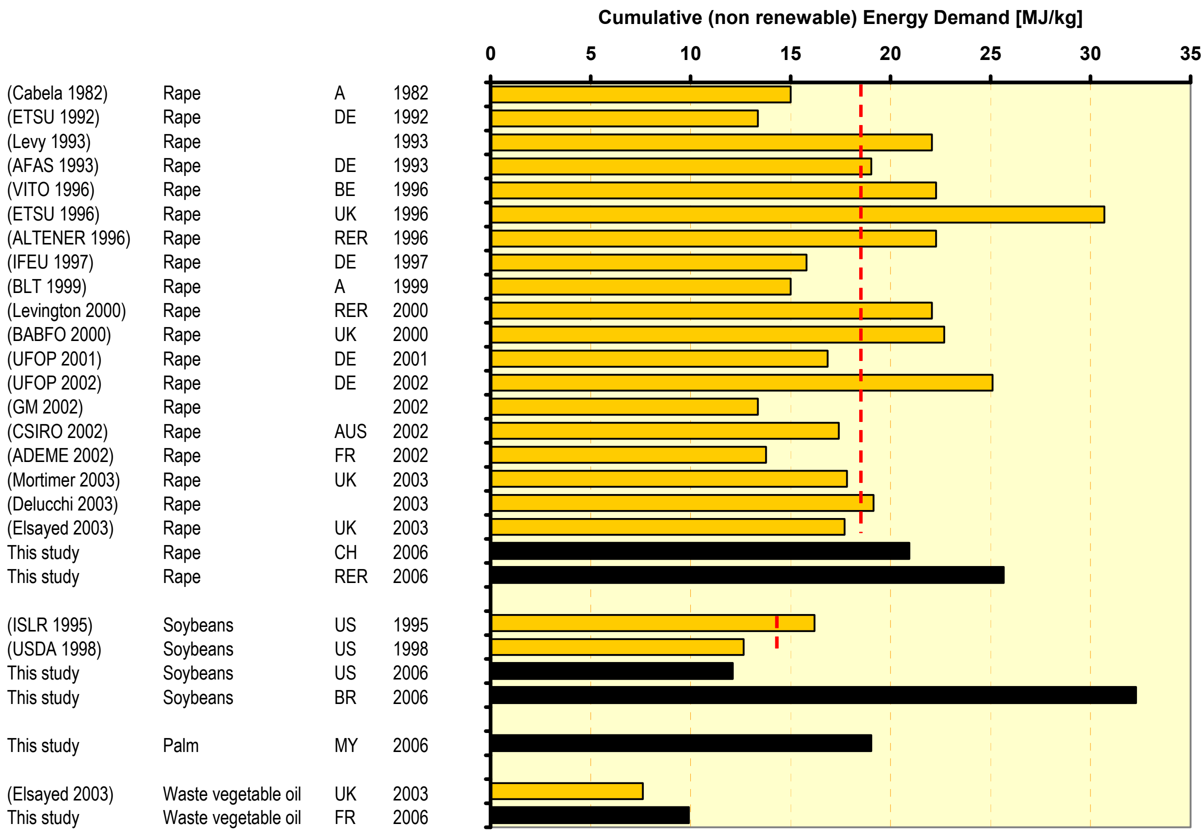


Fig. 17.24 Comparison of CED (non renewable) results with literature data.

The dotted line indicates the average of the literature data considered in the comparison. It shows that the cumulative energy demand obtained in this study is a little higher than the average, but compares rather well with other sources and results. It is very difficult to explain the differences as many factors can influence the results (e.g. inventory data, agricultural practise, technology, plant size, methodology, allocation method, structure and efficiency of energy systems, etc.). On a general basis, the graph shows that the results obtained in this study are coherent with literature data.

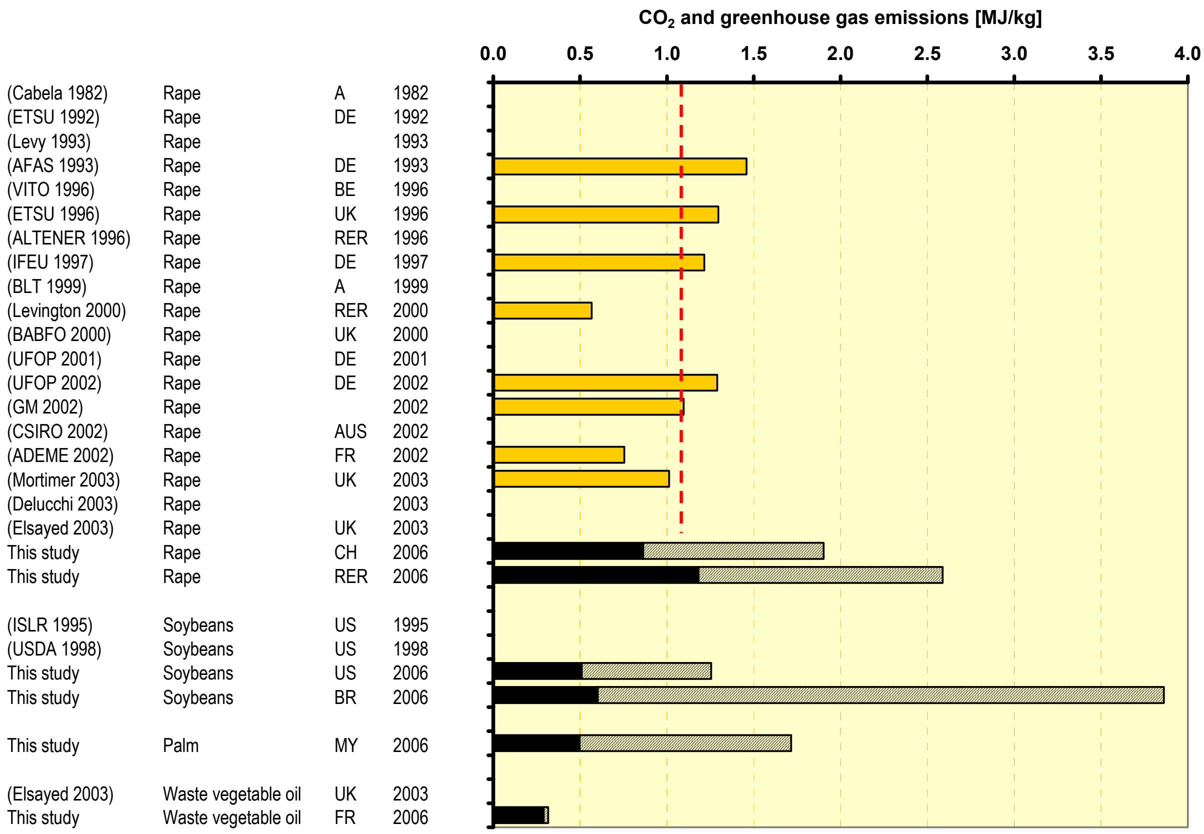


Fig. 17.25 Comparison of CO_2 emissions with literature data.

In the graph above, the "bars" of processes described in this study show both CO_2 only emissions (expressed in kg CO_2 per kg of methyl ester, shown as a solid bar) and total GHG emissions (incl. CO_2 from land transformation). Again, it proved difficult to figure out when literature data were refering to CO_2 only or global GHG emissions. CO_2 of biogenic nature (captured and emitted) is not included (i.e. considered to have a zero global warming potential) in the data presented on the graph above.

Again, the results obtained in this study seem to compare well with literature data. CO_2 only emissions are found to be similar to the literature average in the case of rape methyl ester, i.e. about 1.1 kg CO_2/kg RME. Again, there can be many reasons why the results in the various literature sources should vary, and we will avoid here a tentative explanation as detailed hypotheses are often too limited in the literature. The results, however, are judged satisfactory.

17.17 Conclusions

The production of methyl ester and related datasets is largely determined by the impact of the agricultural phase. Because of the allocation issue, only the carbon balance is satisfied within these datasets. Because allocation, indeed, is done according to the respective economic values of the by-products, it is not possible to satisfy both the carbon and the energy balances. The deviation in terms of energy balance, however, is relatively small and should not be a problem at all when evaluating the environmental impacts.

Drived by environmental concerns, more and more methyl ester producers are choosing wood as the fuel of choice to power esterification plants. This could be considered more seriously when further work on this inventory is carried out. Finally, the company Axens, in collaboration with the Institut Français du Pétrole (IFP) has just developed a novel improved technology for methyl ester production (the so-called ESTERFIP-H process) implemented in the very recent esterification plant in Sète (F). This process could also be investigated in future works.

Abbreviations

% vol.	percentage volume
% wt.	percentage weight
B5	mixture of 5% (vol.) biodiesel with 95% (vol.) conventional diesel
B20	mixture of 20% (vol.) biodiesel with 80% (vol.) conventional diesel
B30	mixture of 30% (vol.) biodiesel with 70% (vol.) conventional diesel
B100	pure (or neat) biodiesel (100% biodiesel)
BLW	Bundesamt für Landwirtschaft (Swiss Federal office for Agriculture)
BR	Brazil
CED	Cumulative Energy Demand
CFPP	cold filter plugging point
CH	Switzerland
CHF	Swiss franc
CI (engine)	compression ignition (engine)
EPFL	Swiss Federal Institute of Technology of Lausanne
EU	European Union
FAME	fatty acid methyl ester
FR	France
GE	Canton of Geneva
GHG	greenhouse gas
H_3PO_4	phosphoric acid
HCl	hydrochloric acid
HHV	higher heating value
kg	kilogram
KOH	potassium hydroxide (also often referred to as 'potash')
IC (engine)	internal combustion (engine)
IFP	Institut Français du Pétrole
IPCC	Intergovernmental Panel for Climate Change
l	litres
LASEN	Laboratory of Energy Systems (EPFL)
LCI	life cycle inventory
LCIA	life cycle inventory assessment
LHV	lower heating value
MJ	megajoules, 10^6 joules
Ml	million litres
MO-process	multi-output process

Mt	million tons
MY	Malaysia
Na_3PO_4	sodium phosphate
NaOH	sodium hydroxide
RER	Europe (region)
RME	rape methyl ester
SME	soybean methyl ester
t	metric tons
US	United States
US$	United States Dollar
VD	Canton of Vaud
VOME	vegetable oil methyl ester
XME	methyl ester (generic acronym)

Glossary of terms

Acid

An acid (often represented by the generic formula AH) is typically a water-soluble, sour-tasting chemical compound. In common usage an acid is any substance that, when dissolved in water, gives a solution with a pH of less than 7. In general scientific usage an acid is a molecule or ion that is able to give up a proton (H^+ ion) to a base, or accept an unshared pair of electrons from a base. An acid reacts with a base in a neutralization reaction to form a salt.

Base

The common (Arrhenius) definition of a base, also known as an alkaline compound, is a chemical compound that either donates hydroxide ions or absorbs hydrogen ions when dissolved in water. Bases and acids are seen as opposites because the effect of an acid is to increase the hydronium ion (H_3O) concentration in water, whereas bases reduce this concentration. Arrhenius bases are water-soluble and these solutions always have a pH greater than 7.

Boiling point

The boiling point of a substance is the temperature at which it can change state from a liquid to a gas throughout the bulk of the liquid. A liquid may change to a gas at temperatures below the boiling point through the process of vaporization. Any change of state from a liquid to a gas at boiling point is considered evaporation. However, evaporation is a surface phenomenon, in which only molecules located near the gas/liquid surface could evaporate. Boiling on the other hand is a bulk process, so at the boiling point molecules anywhere in the liquid may be vaporized, resulting in the formation of vapor bubbles.

Cetane number

Cetane number or CN is to diesel (resp. biodiesel) fuel what octane rating is to gasoline. It is a measure of the fuel's combustion quality. Cetane is an alkane molecule that ignites very easily under compression, so it was assigned a cetane number of 100. All other hydrocarbons in diesel fuel are indexed to cetane as to how well they ignite under compression. The cetane number therefore measures how quickly the fuel starts to burn (auto-ignites) under diesel engine conditions. A fuel with a high cetane number starts to burn shortly after it is injected into the cylinder; it has a short ignition delay period. Conversely, a fuel with a low cetane number resists auto-ignition and has a longer ignition delay period.

Cold Filter Plugging Point (CFPP)

Highest temperature at which a given volume of fuel fails to pass through a standardised filtration device in a specified time, when cooled under standardised conditions.

Distillation

Distillation is a means of separating liquids through differences in their vapor pressures.

Ester

In organic chemistry and biochemistry, esters are organic compounds where an organic group (symbolised by R' in this article) replaces a hydrogen atom (or more than one) in an oxygen acid. An oxygen acid is an acid whose molecule has an -OH group from which the hydrogen (H) can dissociate as an H+ ion. The general formula of an ester of a carboxylic acid is R-COOR'.

Esterification

Esterification is the general name for a chemical reaction in which two chemicals (typically an alcohol and an acid) form an ester as the reaction product.

Flash point

The flash point of a fuel is the lowest temperature at which it can form an ignitable mix with air. At this temperature the vapor may cease to burn when the source of ignition is removed. A slightly higher temperature, the fire point, is defined at which the vapor continues to burn after being ignited. Neither of these parameters is related to the temperatures of the ignition source or of the burning fuel, which are much higher.

Glyceride

Glycerides are esters of glycerol and fatty acids. Glycerol has three hydroxyl functional groups and can esterify with one, two or three fatty acids to form monoglycerides, diglycerides and triglycerides. Vegetable oils and animal fats mostly contain triglycerides, but are broken down by natural enzymes (lipases) into mono- and diglycerides and free fatty acids.

Glycerine (or glycerol)

Glycerine (also glycerin or glycerol), and less commonly as 1,2,3-propanetriol, 1,2,3-trihydroxypropane, glyceritol, and glycyl alcohol is a colorless, odorless, hygroscopic, and sweet tasting viscous liquid. Glycerin has three hydrophilic alcoholic hydroxyl groups (-OH) that are responsible for its solubility in water. Glycerin is prochiral. Glycerin is used in glycerin soap, in cosmetics and creams, in foods, in chemistry, and in glycerin Fog machine mist. Glycerin is produced from dihydroxyacetone phosphate (DHAP) by the enzyme glycerol 3-phosphate dehydrogenase (Gpd p) in the mitochondrion of the eukaryotic cell during glycolysis.

Fatty acid methyl ester (FAME)

A fatty acid methyl ester (FAME) can be created by an alkali catalyzed reaction between fats or fatty acids and methanol. The molecules in biodiesel are primarily FAMEs.

Oxidation

Oxidation describes the loss of an electron by a molecule, atom, or ion. Substances that have the ability to oxidise other substances are said to be oxidative and are known as oxidizing agents, oxidants or oxidizers. Put in another way, the oxidant removes electrons from the substance. Oxidants are usually chemical substances in high oxidation numbers (e.g. H_2O_2, MnO_4^-, CrO_3, OsO_4) or highly electronegative substances that can gain one or two extra electrons by oxidizing a substance (O_2, O_3, F_2, Cl_2, Br_2).

Paraffin

Paraffin is a common name for a group of high molecular weight alkane hydrocarbons with the general formula C_nH_{2n+2}, where n is greater than about 20, discovered by Carl Reichenbach. Paraffin is also a technical name for an alkane in general, but in most cases it refers specifically to a linear, or normal alkane, while branched, or isoalkanes are also called isoparaffins. (Latin para + affinis with the meaning here of "lacking affinity", or "lacking reactivity".

Solvent

A solvent is a liquid that dissolves a solid, liquid, or gaseous solute, resulting in a solution. The most common solvent in everyday life is water. The term organic solvent refers to most other solvents that are organic compounds and contain carbon atoms. Solvents usually have a low boiling point and evaporate easily or can be removed by distillation, thereby leaving the dissolved substance behind. Solvents should therefore not react chemically with the dissolved compounds — they have to be inert.

Transesterification

In organic chemistry, transesterification is the process of exchanging the alkoxy group of an ester compound by another alcohol. These reactions are often catalyzed by the addition of an acid or base. Acids can catalyse the reaction by donating a proton to the alkoxy group, thus making it more reactive, while bases can catalyse the reaction by removing a proton from the alcohol, thus making it more reactive. Transesterification is used in the synthesis of polyester, in which diesters undergo transesterification with diols to form macromolecules. For example, dimethyl terephthalate and ethylene glycol react to form polyethylene terephthalate and methanol, which is evaporated to drive the reaction forward. The reverse reaction (methanolysis) is also an example of transesterification, and has been used to recycle polyesters into individual monomers.

Appendices: EcoSpold Meta Information

Tab. A. 34 EcoSopld Meta Information of the unit processes relating to infrastructure processes, CH.

Field name, IndexNumber	6430	6432
Name	oil mill	vegetable oil esterification plant
Location	CH	CH
InfrastructureProcess	1	1
Unit	unit	unit
Type	1	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes land use and occupation, buildings and facilities of a typical industrial oil mill in the Swiss context. Storage of the seeds is included in the infrastructure. Energy use for construction and related emissions and/or waste effluents are not included.	This process includes land use and occupation, buildings and facilities of a typical industrial vegetable oil esterification plant in the Swiss context. Energy use for construction and related emissions and/or waste effluents are not included.
Amount	1	1
LocalName	Ölmühle	Pflanzenölveresterungsanlage
Synonyms		
GeneralComment	Oil mill with a daily production of 63 t vegetable oil. Life time of plant taken as 50 years.	Esterification plant with a daily production of 63 t methyl ester. Life time of plant taken as 50 years.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1998	1998
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1998, based on pilot scale biodiesel plant in CH, in operation	Data from 1998, based on pilot scale biodiesel plant in CH, in operation
Text	Data from biodiesel producer in CH, adapted to the plant size considered.	Data from biodiesel producer in CH, adapted to the plant size considered.
Text	Typical oil mill designed for vegetable oil extraction (for use in the biodiesel industry), with pre-pressing of rape seeds, Swiss context.	Typical vegetable oil esterification plant designed for methyl ester production (for use in the vehicle fuels market) adapted to Swiss conditions and context, CH, vegetable oil base-catalyzed transesterification facility.
Percent	0	0
ProductionVolume	Production of rape oil for biodiesel was approx. 2 kt in 2004 in CH	Total production of methyl ester was 2.5-3 kt in 2004 in CH
SamplingProcedure	Adapted to reference capacity with data from one plant in CH	Adapted to reference capacity with data from one plant in CH
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 35 **EcoSopId Meta Information of the datasets relating to rape oil and methyl ester, CH.**

Field name, IndexNumber	6501	6433
Name	rape seeds, in oil mill	rape oil, in esterification plant
Location	CH	CH
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	5
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the transport of rape seeds to the mill, and the processing of the seeds to rape oil and rape meal. The oil extraction refers to the cold-press extraction technique. System boundary is at the oil mill.	This process includes the esterification process of oil to methyl ester and glycerine, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1
LocalName	Rapskörner, in Ölmühle	Rapsöl, in Veresterung
Synonyms		
GeneralComment	Inventory refers to the production of 1 kg rape oil, respectively rape meal. The multioutput-process 'rape seeds, in oil mill' delivers the co-products 'rape oil, at oil mill' and 'rape meal, at oil mill'. Economic allocation with allocation factor of 74.3% to rape oil. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg rape rape methyl ester, respectively glycerine, from rape oil. The multioutput-process 'rape oil, in esterification plant' delivers the co-products 'rape methyl ester, at esterification plant' and 'glycerine, from rape oil, at esterification plant'. Economic allocation with allocation factor of 92.9% to rape oil. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1998	1998
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1998 to 2006, current technology in CH	Data from 1998 to 2006, current technology in CH
Text	Data from biodiesel producers in CH, industrial data	Data from biodiesel producers in CH, industrial data
Text	Cold pressing of rape seeds in a standard oil press (based on the EcoEnergie Etoy biodiesel pilot plant, CH), Swiss context.	Typical rape oil esterification plant designed for rape methyl ester (RME) production (for use in the vehicle fuels market), Swiss context. Rape oil base-catalyzed transesterification (based on industrial data from biodiesel producer in CH).
Percent	0	0
ProductionVolume	Approx. 6 kt of rape seeds were processed to biodiesel in 2004 in CH	Approx. 2.5-3 kt of vegetable oil were processed to methyl ester in 2004 in CH
SamplingProcedure	Data from various biodiesel producers in CH, industrial data	Data from biodiesel producers in CH, industrial data
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 36 EcoSopId Meta Information of the datasets relating to rape oil and methyl ester, RER.

Field name, IndexNumber	6879	6881
Name	rape seeds, in oil mill	rape oil, in esterification plant
Location	RER	RER
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	5
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the transport of rape seeds to the mill, and the processing of the seeds to rape oil and rape meal. The oil extraction refers to the solvent extraction technique. System boundary is at the oil mill.	This process includes the esterification process of oil to methyl ester, glycerine and potassium sulphate, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1
LocalName	Rapskörner, in Ölmühle	Rapsöl, in Veresterung
Synonyms		
GeneralComment	Inventory refers to the production of 1 kg rape oil, respectively rape meal. The multioutput-process 'rape seeds, in oil mill' delivers the co-products 'rape oil, at oil mill' and 'rape meal, at oil mill'. Economic allocation with allocation factor of 74.3% to rape oil. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg rape rape methyl ester, respectively glycerine and potassium sulphate, from rape oil. The multioutput-process 'rape oil, in esterification plant' delivers the co-products 'rape methyl ester, at esterification plant', 'glycerine, from rape oil, at esterification plant', 'potassium sulphate, as K2O, from rape oil, at esterification plant'. Economic allocation with allocation factor of 86.9% to rape oil, 12.9% to glycerine and 0.2% to potassium sulphate. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1996	2004
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1996 to 2003, current technology in the EU	Data from 1996 to 2003, current technology in the EU
Text	Data from different plants worldwide, mostly in Europe (incl. literature data)	Data from different plants worldwide (incl. literature data)
Text	Typical oil mill designed for rape oil solvent extraction, with pre-pressing of rape seeds, European context.	Typical vegetable oil esterification plant designed for the production of methyl ester (for use in the vehicle fuels market), global context. Base-catalyzed transesterification.
Percent	0	0
ProductionVolume	Approx. 8100 kt of rape seeds were processed to RME in 2005 in the EU	Approx. 2'000 kt of rape oil were processed to RME in 2004 in the EU
SamplingProcedure	Cross-checking of various literature sources from 1998 to 2006	Cross-checking of various literature sources from 1998 to 2006
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 37 EcoSpold Meta Information of the unit processes relating to palm oil and methyl ester, MY.

Field name, IndexNumber	6875	6877
Name	palm fruit bunches, in oil mill	palm oil, in esterification plant
Location	MY	MY
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	5
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the extraction of palm oil, palm kernel oil and palm kernel meal, from palm fruit bunches. Energy supply from extracted solids (fibres, shells, digester solids and empty fruit bunches) and treatment of specific wastewater effluents are taken into account. System boundary is at the oil mill.	This process includes the esterification process of palm oil to methyl ester and glycerine, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1
LocalName	Palmfruchtstände, in Ölmühle	Palmöl, in Veresterung
Synonyms		
GeneralComment	Inventory refers to the production of 1 kg palm oil, respectively palm kernel oil and palm kernel meal, from palm oil. The multioutput-process 'palm fruit bunches, in oil mill' delivers the co-products 'palm oil, at oil mill', 'palm kernel oil, at oil mill' and 'palm kernel meal, at oil mill'. Economic allocation with allocation factor of 81.3% to palm oil, 17.3% to palm kernel oil, and 1.4% to palm kernel meal. Allocation of CO2 emissions is done according to carbon balance.	Inventory refers to the production of 1 kg palm methyl ester (PME), respectively glycerine, from palm oil. The multioutput-process 'palm oil, in esterification plant' delivers the co-products 'palm methyl ester, at esterification plant' and 'glycerine, from palm oil, at esterification plant'. Economic allocation with allocation factor of 87.1% to rape oil and 12.9% to glycerine. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1995	1996
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1995 to 2006, current technology for palm oil mills in MY	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
Text	Data from various literature references (incl. specific Malaysian and Indonesian industrial data)	Data from different plants worldwide (incl. literature data)
Text	Typical palm oil mill designed for palm oil and palm kernel oil extraction, Malaysian context. Palm fuit bunches undergo sterilization, stripping, digestion, oil extraction, screening, settling and refining.	Typical vegetable oil esterification plant designed for the production of methyl ester (for use in the vehicle fuels market), global context. Base-catalyzed transesterification.
Percent	0	0
ProductionVolume	Processing of fresh palm fruit bunches was 76 Mt in 2005 in MY	Production of palm methyl ester was marginal in 2005 in MY
SamplingProcedure	Cross-checking of various literature sources from 1998 to 2006	Cross-checking of various literature sources from 1998 to 2006
Extrapolations	Direct emissions (resulting from the combustion of sorghum bagasse) are based on the the combustion of wood chips (without emission control), according to the corresponding dry matter content, carbon content and energy content.	The dataset "electricity, medium voltage, production NL" is used as a proxy for electricity supply in MY, because it is the mix, closest to the electricity mix in MY.
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 38 EcoSpold Meta Information of the unit processes relating to soybean oil and methyl ester, US.

Field name, IndexNumber	32026	32029
Name	soybeans, in oil mill	soybean oil, in esterification plant
Location	US	US
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	5
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the transport of soybeans to the mill, and the processing of soybeans to soybean oil and meal. System boundary is at the oil mill.	This process includes the esterification process of soybean oil to methyl ester and glycerine, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1
LocalName	Sojabohnen, in Ölmühle	Sojaöl, in Veresterung
Synonyms		
GeneralComment	Inventory refers to the production of 1 kg soybean oil, respectively soybean meal (incl. hulls). The multioutput-process 'soybeans, in oil mill' delivers the co-products 'soybean oil, at oil mill' and 'soybean meal, at oil mill'. Economic allocation with allocation factor of 34.5% to oil and 65.5 to meal. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg soybean methyl ester, respectively glycerine, from soybean oil. The multioutput-process 'soybean oil, in esterification plant' delivers the co-products 'soybean methyl ester, at esterification plant' and 'glycerine, from soybean oil, at esterification plant'. Economic allocation with allocation factor of 92.0% to soybean oil and 8.0% to glycerine. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1998	1996
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1998 to 2005, current technology for soybean oil extraction	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
Text	Data from an industrial oil mill in the US, described in US study	Data from different plants worldwide (incl. literature data)
Text	Typical oil mill designed for soybean oil solvent extraction (incl. pre-cracking of soybeans, dehulling, oil extraction, meal processing and oil purification), US context.	Typical vegetable oil esterification plant designed for the production of methyl ester (for use in the vehicle fuels market), global context. Base-catalyzed transesterification.
Percent	0	0
ProductionVolume	Approx. 46 Mt of soybeans were processed to oil and meal in 2003 in the US	Production of soybean methyl ester reached 300 kt in 2005 in the US
SamplingProcedure	Data from US study, cross-checking with various literature sources, industrial data. Sources of energy supply from national statistics.	Cross-checking of various literature sources from 1998 to 2006
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 39 EcoSopld Meta Information of the unit processes relating to soybean oil and methyl ester, BR.

Field name, IndexNumber	32033	32036
Name	soybeans, in oil mill	soybean oil, in esterification plant
Location	BR	BR
InfrastructureProcess	0	0
Unit	kg	kg
Type	5	5
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the transport of soybeans to the mill, and the processing of soybeans to soybean oil and meal. System boundary is at the oil mill.	This process includes the esterification process of soybean oil to methyl ester and glycerine, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1
LocalName	Sojabohnen, in Ölmühle	Sojaöl, in Veresterung
Synonyms		
GeneralComment	Inventory refers to the production of 1 kg soybean oil, respectively soybean meal (incl. hulls). The multioutput-process 'soybeans, in oil mill' delivers the co-products 'soybean oil, at oil mill' and 'soybean meal, at oil mill'. Economic allocation with allocation factor of 40.7% to oil and 59.3 to meal. Allocation is done according to carbon balance for CO2 emissions.	Inventory refers to the production of 1 kg soybean methyl ester, respectively glycerine, from soybean oil. The multioutput-process 'soybean oil, in esterification plant' delivers the co-products 'soybean methyl ester, at esterification plant' and 'glycerine, from soybean oil, at esterification plant'. Economic allocation with allocation factor of 92.0% to soybean oil and 8.0% to glycerine. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	1998	1996
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1998 to 2005, current technology for soybean oil extraction	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
Text	Data from an industrial oil mill in the US, based mostly on one literature source	Data from different plants worldwide (incl. literature data)
Text	Typical oil mill designed for soybean oil solvent extraction (incl. pre-cracking of soybeans, dehulling, oil extraction, meal processing and oil purification), US context.	Typical vegetable oil esterification plant designed for the production of methyl ester (for use in the vehicle fuels market), global context. Base-catalyzed transesterification.
Percent	0	0
ProductionVolume	Approx. 50 Mt of soybeans were processed to oil and meal in 2005 in BR	Production of soybean methyl ester marginal in 2005 in BR
SamplingProcedure	Data from US study, cross-checking with various literature sources, industrial data. Sources of energy supply from national statistics.	Cross-checking of various literature sources from 1998 to 2006
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 40 EcoSopId Meta Information of the unit processes relating to vegetable oil, from waste cooking oil.

Field name, IndexNumber	6431	6810	6878
Name	vegetable oil, from waste cooking oil, at plant	vegetable oil, from waste cooking oil, at plant	vegetable oil, from waste cooking oil, in esterification plant
Location	CH	FR	FR
InfrastructureProcess	0	0	0
Unit	kg	kg	kg
Type	1	1	5
Version	2.0	2.0	2.0
energyValues	0	0	0
LanguageCode	en	en	en
LocalLanguageCode	de	de	de
Person	65	65	65
QualityNetwork	1	1	1
DataSetRelatesToProduct	1	1	1
IncludedProcesses	This process includes the collection of waste vegetable oil and delivery to the treatment plant, treatment for impurities and water removal, conditioning and storage of the oil. Treatment of effluents is taken into account. Includes also the gross calorific value of the biomass and the carbon dioxide credit. System boundary is at the oil refining facility.	This process includes the collection of waste vegetable oil and delivery to the treatment plant, treatment for impurities and water removal, conditioning and storage of the oil. Treatment of effluents is taken into account. Includes also the gross calorific value of the biomass and the carbon dioxide credit. System boundary is at the oil refining facility.	This process includes the esterification process of vegetable oil (from waste cooking oil) to methyl ester and glycerine, intermediate storage of the oil and products, treatment of specific wastewater effluents. System boundary is at the esterification plant.
Amount	1	1	1
LocalName	Pflanzenöl, aus Altspeiseöl, ab Aufbereitung	Pflanzenöl, aus Altspeiseöl, ab Aufbereitung	Pflanzenöl, aus Altspeiseöl, in Veresterung
Synonyms	SVO//straight vegetable oil//pure vegetable oil//vegetable oil	SVO//straight vegetable oil//pure vegetable oil//vegetable oil	
GeneralComment	Treated vegetable oil consists of 93.7% triglycerides and 6.7% fatty acid methyl ester. Process refers to the acid-catalysed esterification of free fatty acids and includes water removal, glycerine washing and methanol recovery.	Treated vegetable oil consists of 93.7% triglycerides and 6.7% fatty acid methyl ester. Process refers to the acid-catalysed esterification of free fatty acids and includes water removal, glycerine washing and methanol recovery.	Inventory refers to the production of 1 kg vegetable oil methyl ester (VOME), respectively glycerine, from purified waste cooking oil. The multioutput-process 'vegetable oil, from waste cooking oil, in esterification plant' delivers the co-products 'vegetable oil methyl ester, at esterification plant' and 'glycerine, from vegetable oil, at esterification plant'. Economic allocation with allocation factor of 87.1% to rape oil and 12.9% to glycerine. Allocation of CO2 emissions is done according to carbon balance.
InfrastructureIncluded	1	1	1
Category	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	C57H102O7	C57H102O6	
StatisticalClassification			
CASNumber			
StartDate	2003	2003	1996
EndDate	2006	2006	2006
DataValidForEntirePeriod	1	1	1
OtherPeriodText	Data from 2003, existing technology	Data from 2003, existing technology	Data from 1996 to 2003, current technology for large scale biodiesel plants worldwide
Text	Data is mostly from one literature source (US), adapted to vegetable oil treatment in CH.	Data is mostly from one literature source (US), adapted to vegetable oil treatment in FR.	Data from different plants worldwide (incl. literature data)
Text	Acid-catalysed esterification of free-fatty acids.	Acid-catalysed esterification of free-fatty acids.	Typical vegetable oil esterification plant designed for vegetable oil methyl ester (VOME) production (for use in the vehicle fuels market), in the French context. Vegetable oil base-catalyzed transesterification.
Percent	0	0	0
ProductionVolume	Waste cooking oil recycled represents 14'000 t/yr out of 100'000 t/yr.	Not known	Overall production of methyl ester was about 500 kt in 2005 in France
SamplingProcedure	Data mostly from one literature source (US).	Data mostly from one literature source (US).	Cross-checking of various literature sources from 1998 to 2006
Extrapolations	none	none	none
UncertaintyAdjustments	none	none	none
Person	67	67	67
DataPublishedIn	2	2	2
ReferenceToPublishedSource	40	40	40
Copyright	1	1	1
AccessRestrictedTo	0	0	0
CompanyCode			
CountryCode			
PageNumbers	oil-based biofuels	oil-based biofuels	oil-based biofuels
Validator	41	41	41
Details	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none

Tab. A. 41 EcoSpold Meta Information of the unit processes relating to methyl ester distribution, production CH.

Field name, IndexNumber	6308	6434
Name	rape oil, at regional storage	rape methyl ester, at regional storage
Location	CH	CH
InfrastructureProcess	0	0
Unit	kg	kg
Type	1	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This process includes the transport of rape oil from the oil mill to the end user. Operation of storage tanks and equipment. Emissions from evaporation and treatment of effluents.	This process includes the transport of rape methyl ester from the esterification plant to the end user. Operation of storage tanks and fuel station. Emissions from evaporation and treatment of effluents.
Amount	1	1
LocalName	Rapsöl, ab Regionallager	Rapsölmethylester, ab Tankstelle
Synonyms		RME
GeneralComment	Inventory refers to the distribution of 1 kg of rape oil in Switzerland. Rape oil is produced in Switzerland. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of rape methyl ester (RME) in Switzerland. RME is produced in Switzerland. Distribution to the final consumer (service station) including all necessary transports.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	2004	2004
EndDate	2008	2008
DataValidForEntirePeriod	1	1
OtherPeriodText		
Text	Surveys mainly for DE and CH.	Surveys mainly for DE and CH.
Text	Distribution of fuels	Distribution of fuels
Percent	0	0
ProductionVolume	Total production of rape oil was approx. 18-20 kt in 2004 in CH	Total production of methyl ester was 2.5-3 kt in 2004 in CH
SamplingProcedure	Environmental reports and literature.	Environmental reports and literature.
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	oil-based biofuels	oil-based biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 42 EcoSopId Meta Information of the unit processes relating to methyl ester distribution, imports CH.

Field name, IndexNumber	6809	6812	6815	32032	32039
Name	palm methyl ester, production MY, at service station	vegetable oil methyl ester, production FR, at service station	rape methyl ester, production RER, at service station	soybean methyl ester, production US, at service station	soybean methyl ester, production BR, at service station
Location	CH	CH	CH	CH	CH
InfrastructureProcess	0	0	0	0	0
Unit	kg	kg	kg	kg	kg
Type	1	1	1	1	1
Version	2.0	2.0	2.0	2.0	2.0
energyValues	0	0	0	0	0
LanguageCode	en	en	en	en	en
LocalLanguageCode	de	de	de	de	de
Person	65	65	65	65	65
QualityNetwork	1	1	1	1	1
DataSetRelatesToProduct	1	1	1	1	1
IncludedProcesses	This dataset includes the transport of palm (oil) methyl ester (PME) from esterification plants in Malaysia to Switzerland (11700 km by tanker, 500 km by train, 100 km by truck), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of (waste) vegetable oil methyl ester (VOME) from esterification plants in France to Switzerland (600 km by rail, 50 km by truck), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of rape methyl ester (RME) from esterification plants in RER (Germany, France, Austria, Italy, Czech Republic) to Switzerland (650 km by rail, 150 km by truck), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of soybean methyl ester (SME) from esterification plants in US to Switzerland (1400 km by rail, 100 km by truck, 7000 km by tanker, 840 km by barge), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.	This dataset includes the transport of soybean methyl ester (SME) from esterification plants in BR to Switzerland (500 km by rail, 150 km by truck, 10000 km by tanker, 840 km by barge), and distribution to the end user (100 km by rail and 150 km by road). Operation of storage tanks and fuel station is included. Emissions from evaporation and treatment of effluents are also included.
Amount	1	1	1	1	1
LocalName	Palmölmethylester, Produktion MY, ab Tankstelle	Pflanzenölmethylester, Produktion FR, ab Tankstelle	Rapsölmethylester, Produktion RER, ab Tankstelle	Sojaölmethylester, Produktion US, ab Tankstelle	Sojaölmethylester, Produktion BR, ab Tankstelle
Synonyms	XME//PME//biodiesel//bio-diesel	XME//VOME//biodiesel//bio-diesel	RME//biodiesel//bio-diesel	XME//SME//biodiesel//bio-diesel	XME//SME//biodiesel//bio-diesel
GeneralComment	Inventory refers to the distribution of 1 kg of palm methyl ester (PME) in Switzerland. PME is imported from Malaysia and produced from palm oil. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of vegetable oil methyl ester (VOME) in Switzerland. VOME is imported from France and produced from waste vegetable oil. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of rape methyl ester (RME) in Switzerland. RME is imported from the European Union (EU) and produced from rape oil. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of soybean methyl ester (SME) in Switzerland. SME is imported from the US and produced from soybean oil. Distribution to the final consumer (service station) including all necessary transports.	Inventory refers to the distribution of 1 kg of soybean methyl ester (SME) in Switzerland. SME is imported from BR and produced from soybean oil. Distribution to the final consumer (service station) including all necessary transports.
InfrastructureIncluded	1	1	1	1	1
Category	biomass	biomass	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	C17H33O3	C19H35O2	C19H35O2	C19H35O2	C19H35O2
StatisticalClassification					
CASNumber			073891-99-3		
StartDate	2004	2004	2004	2004	2004
EndDate	2008	2008	2008	2008	2008
DataValidForEntirePeriod	1	1	1	1	1
OtherPeriodText					
Text	Transport to Malaysian harbour (100 km by road), and then oversea to Marseille harbour (11700 km by tanker). Delivery from Marseille to Geneva (500 km by train), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Delivery to Geneva or Basel (600 km by rail and 50 km by road), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Delivery to Geneva or Basel (650 km by rail and 150 km by road), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Transport through US to East Coast harbour (1400 km by rail and 100 km by road), and then oversea to Rotterdam harbour (7000 km by tanker). Delivery from Rotterdam to Basel (840 km by barge), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.	Transport through BR to East Coast harbour (500 km by rail and 150 km by road), and then oversea to Rotterdam harbour (10000 km by tanker). Delivery from Rotterdam to Basel (840 km by barge), and distribution in CH (100 km by rail and 150 km by road). Surveys for distribution mainly for DE and CH.
Text	Distribution of fuels	Distribution of fuels	Distribution of fuels	Distribution of fuels	Distribution of fuels
Percent	0	0	0	0	0
ProductionVolume	Production of biodiesel for use as a fuel was marginal in 2005 in MY	Production of biodiesel for use as a fuel was about 500 kt in 2005 in France	Production of biodiesel for use as a fuel was about 3200 kt in 2005 in the EU	Production of biodiesel for use as a fuel was about 300 kt in 2005 in the EU	Production of biodiesel for use as a fuel was marginal in 2005 in BR
SamplingProcedure	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.	Environmental reports and literature. Calculation of freight distances.
Extrapolations	none	none	none	none	none
UncertaintyAdjustments	none	none	none	none	none
Person	67	67	67	67	67
DataPublishedIn	2	2	2	2	2
ReferenceToPublishedSource	40	40	40	40	40
Copyright	1	1	1	1	1
AccessRestrictedTo	0	0	0	0	0
CompanyCode					
CountryCode					
PageNumbers	oil-based biofuels	oil-based biofuels	oil-based biofuels	oil-based biofuels	oil-based biofuels
Validator	41	41	41	41	41
Details	automatic validation	automatic validation	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none	none	none

References

Althaus et al. 2004	Althaus H.J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A. (2004). Life Cycle Inventories of Chemicals. Final report ecoinvent 2000 No. 8. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Ballestra 2003	Ballestra, Adami I. (2003). Three steps towards biodiesel. In: Oils & Fats International, November 2003.
Beer et al. 2001	Beer T., et al. (2001). Comparison of transport fuels. Life-cycle emissions analysis of alternative fuels for heavy vehicles. Prepared for the Australian Greenhouse Office, by CSIRO, in collaboration with the University of Melbourne and RMIT Center for Design.
Bendz 2005	Bendz K. (2005). EU25 Oilseeds and products: Biofuels situation in the European Union. Global Agriculture Information Network, GAIN voluntary report No. E35058, March 23, 2005.
Bockey 2004	Bockey D. (2004). Policy initiative schemes and benefit of biofuel promotion in Germany: Current status of legislation and production. Conference on biofuels : Challenges for Asian future, Queen Sirikit National Convention Center, Bangkok, Thailand.
Buczek & Czepirski 2004	Buczek B. and Czepirski L. (2004). Applicability of used rapeseed oil for production of biodiesel. In: Inform, Industrial oil products, Vol. 15 (3), pp. 186-188, March 2004.
Ceuterick et al. 1997	Ceuterick, D. & Spirinckx, C. (1997). Comparative LCA of biodiesel and fossil diesel fuel. Final report No. 1997/PPE/R/026, VITO, Flemish Institute for Technological Research, Mol, Belgium.
Choo & Ma 1996	Choo Y.M. & Ma A.N. (1996). Production technology of methyl esters from palm and palm kernel oils. In: PORIM technology, No.18, June 1996. © Palm Oil Research Institute of Malaysia, 1996.
Choo et al. 1995	Choo Y.M., Ma A.N. & Yusof B. (1995). Production and evaluation of palm oil methyl esters as diesel substitute. In: Journal of Oil Palm Research, Special Issue, pp. 15-25, November 1995. © Malaysian Palm Oil Board.
Choo et al. 2005	Choo Y.M., Ma A.N., Chan K.W. & Yusof B. (2005). Palm diesel: An option for greenhouse gas mitigation in the energy sector. In: Journal of Oil Palm Research, Vol. 17, pp. 47-52, June 2005. © Malaysian Palm Oil Board.
Choo et al. 2005	Choo Y.M. et al. (2005). Palm diesel: Green and renewable fuel from palm oil. © Malaysian Palm Oil Board 2005
Dauriat et al. 2001	Dauriat A., Fromentin A., Sarlos G. (2001). Possibilités d'utilisation de biocarburants à l'Aéroport International de Genève. Rapport 140.104, préparé par le Laboratoire de Systèmes Energétiques (LASEN) de l'EPFL pour l'Aéroport International de Genève, avec la collaboration du GECOS, EPFL et Fromentin Bioenergy Consulting.
Delucchi & Lipman 2003	Delucchi M.A. and Lipman T. (2003). A lifecycle emissions model (LEM): Lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials. Report UCD-ITS-RR-03-17A, Institute of Transportation Studies, University of California, Davis, CA, US. Retrieved from: www.its.ucdavis.edu/publications.html (ref. 2005).
Dreier 1999	Dreier T. (1999). Biogener Kraftstoffe: Energetische, ökologische und ökonomische Analyse. IFE Schriftenreihe Heft No. 38, Lehrstuhl für Energiewirtschaft und Anwendungstechnik, TU München.

Dreier 2000	Dreier T. (2000). Ganzheitliche Systemanalyse und Potenziale biogener Kraftstoffe. IFE Schriftenreihe Heft No. 42, Lehrstuhl für Energiewirtschaft und Anwendungstechnik, TU München.
Dreier et al. 1998	Dreier T., Geiger B. & Saller A. (1998). Ganzheitliche Prozesskettenanalyse für die Erzeugung und Anwendung von biogenen Kraftstoffen. Lehrstuhl für Energiewirtschaft und Anwendungstechnik, TU München, Studie im Auftrag der Daimler Benz AG und des Zentrums für Angewandte Energieforschung in Bayern (ZAE).
EBB 2006	European Biodiesel Board (2006). Statistics of the EU biodiesel industry. Consulted on 11.05.2006 on the internet site of the European Biodiesel Board (EBB) (www.ebb-eu.org).
EIA 2005	Energy Information Administration (2005). Energy consumption by sector. Manufacturing inputs for heat, power, and electricity generation by end use, 2002. In: Annual Energy Review 2004. Report No. DOE-EIA-0384(2004), 15 August 2005.
EurObserv'ER 2005	EurObserv'ER (2005). Biofuels Barometer, June 2005. In: Systèmes Solaires No. 167, June 2005.
Frischknecht et al. 2002	Frischknecht R. & Jungbluth N. (2002). Qualitätsrichtlinien ecoinvent 2000. Arbeitspapier v5.4, Schweizer Zentrum für Ökoinventare, Dübendorf, CH.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. & Spielmann M. (2004). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
GTZ 1997	Deutsche Gesellschaft für Technische Zusammenarbeit (1997). Environmental management guideline for the palm oil industry. Thailand, September 1997. IP-Institut für Projektplanung GmbH on behalf of GTZ.
Henson 1997	Henson I.E. (1997). Analysis of palm oil productivity: 1. The estimation of seasonal trends in bunch dry matter production. In: Journal of Oil Palm Research, Vol. 2, pp. 69-77, December 1997. © Malaysian Palm Oil Board.
Hoh 2006	Hoh R. (2006). Malaysia oilseeds and products, Update (March). GAIN Report No. MY6011, Foreign Agricultural Service, US Department of Agriculture, 6/3 2006.
IEA 2004	IEA (2004). Biofuels for transport. An nternationa perspective. Prepared by the International Energy Agency (IEA), Paris, April 2004.
Jossart 2003	Jossart J.-M. (2003). Les biocarburants en Wallonie. Rapport réalisé dans le cadre du projet "Filière Agriculture et Ressources Renouvelables en Wallonie", avec le soutien du Ministère de la région wallonne - Direction Générale de l'Agriculture, Valbiom, UCL.
Jungbluth 2004	Jungbluth N. (2004). Erdöl. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Hirsinger et al. 1995a	Hirsinger F., Schick K.P., Schul W. & Stalmans M. (1995a). A Life-Cycle Inventory for the Production of Detergent-grade Alcohols. In: Tenside Surf. Det., 32(5), pp. 398 - 410.

Hirsinger et al. 1995b	Hirsinger F., Schick K.P. & Stalmans M. (1995b). A Life-Cycle Inventory for the Production of Oleochemical Raw Materials. In: Tenside Surf. Det., 32(5), pp. 420 - 432.
IEA 2004	IEA (2004). Biofuels for transport. An international perspective. Prepared by the International Energy Agency (IEA), Paris, April 2004.
Kaltschmidt 1997	Kaltschmitt M. & Reinhard G. A. (1997). Nachwachsende Energieträger: Grundlagen, Verfahren, Ökologische Bilanzierung. Vieweg, ISBN/ISSN 3-528-06778-0, Braunschweig, Wiesbaden.
Kittikun et al. 2000	Kittikun A.H., Prasertsan P., Srisuwan G & Krause A. (2000). Environmental management for palm oil mill. Department of Industrial Biotechnology, Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Thailand
Kraus 1999	Kraus K., Niklas G. & Trappe M. (1999). Aktuelle Bewertung des Einsatzes von Rapsöl/RME im Vergleich zu Dieselkraftstoff. UBA-Texte No. 79/99, Umweltbundesamt, www.umweltbundesamt.de (ref. 2005), Berlin.
LBST 2002	L-B-Systemtechnik GmbH (2002). GM well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems: A European study. Prepared by L-B-Systemtechnik and sponsored by GM, LBST, BP, ExxonMobil, Shell, TotalFinaElf.
Ma et al. 2003	Ma A.N, Choo Y.M. & Cheah K.Y. (2003). Development of renewable energy in Malaysia. Malaysian Palm Oil Board, Ministry of Plantation Industries and Commodities, Malaysia.
Mattson et al. 2000	Mattson B., Cederberg C. & Blix L. (2000). Agricultural land use in LCA: case studies of three vegetable oil crops. In: Journal of Cleaner Production 8 (2000) pp. 283-292.
Mehlin et al. 2003	Mehlin M., et al. (2003). Renewable fuels for cross-border transportation. Prepared ba the German Aerospace Centre (Institute of Transport Research), Institue for Energy and Environment and the University of Stuttgart /Institute for Road and Transportation Science), for the European Commission, Directorate General for Environment, June 2003.
Mortimer et al. 2003	Mortimer N.D., Cormack P., Elsayed M.A., Horne R.E. (2003). Evaluation of the comparative energy, global warming and socio-economic costs and benefits of biodiesel. Report No. 20/1, prepared for the Department for Environment, Food and Rural Affairs, Resources research unit, School of Environment and Development, Sheffield Hallam University.
MPOB 2006	Malaysian Palm Oil Board (2006). A summary on the performance of the Malaysian oil palm industry. Retrieved from the MPOB website on 12.05.2006 at: http://econ.mpob.gov.my/economy/summary_latest05.htm.
Nemecek et al. 2004	Nemecek T., Heil A., Huguenin O., Meier S., Erzinger S., Blaser S., Dux. D. and Zimmermann A. (2004). Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent 2000 No. 15. Agroscope FAL Reckenholz and FAT Taenikon, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
O’Connor 2004a	O’Connor (2004). Biodiesel in North-America: Implementation Issues. Prepared by (S&T)2 Consultants Inc. for IEA Bioenergy Task 39, Februara 28, 2004.
O’Connor 2004b	O’Connor (2004). Economic, financial, social analysis and public policies for biodiesel: Phase 1. Prepared by (S&T)2 Consultants Inc. and Meyers Norris Penny LLP, for Natural Resources Canada, Office of Energy Efficiency, November 22, 2004.
Partenaires Diester 2005	Partenaires Diester (2005). Diester: Notre énergie pour l’environnement.

Patyk et al. 2000	Patyk A., Reinhardt A. & Jungk N.C. (2000). Bioenergy for Europe : Which ones fit best? A comparative analysis for the Community. Research funded by The European Commission in the framework of the FAIR V Programme, contract CT 98 3832, November 2000.
Pimentel & Patzek 2005	Pimentel D. & Patzek T. (2005). Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. In: Natural Resources Research, Vol. 14, No. 1, pp. 65-76.
Provance 2003	Provance P. (2003). EU: Biodiesel industra expanding use of of oilseeds. Production Estimates and Crop Assessment Division, Foreign Agricultural Service, US Department of Agriculture, September 20, 2003.
Rinaldi & Hergé 1998	Rinaldi M. & Hergé E. (1998). Esters d'huiles végétales suisses utilisées comme carburant pour moteur diesel: Les premiers résultats d'exploitation sont positifs. Rapport FAT No. 514, Station Fédérale de recherche en économie et technologie agricoles (FAT), 1998 (http://www.fat.admin.ch/f/publi/fb/fatb514f.html).
Scharmer et al. 1996	Scharmer K., Gosse G., Gabrielle B., Golbs G., Lambert L., Poschmann T., Rodenbrock A. & Zimalla K. (1996) Energy balance, ecological impact and economics of vegetable oil methylester production in Europe as substitute for fossil diesel. ALTENER Programme, Contract No. 4.1030/E/94-002-1, GET - Gesellschaft für Entwicklungstechnologie, Jülich.
Schmidt 2004	Schmidt J. (2004). The importance of system boundaries for LCA on large material flows of vegetable oils Text version of poster presented to the Fourth World SETAC Congress, 14-18. November, 2004, Portland, Oregon, USA.
Schöpe et al. 2002	Schöpe M. and Britschkat G. (2002). Macroeconomic evaluation of rape cultivation for biodiesel production in Germany. Preliminary report from Ifo Schnelldienst No.6, Institüt für Wirtschaftsorschung, München, Germany.
Sheehan et al. 1998a	Sheehan J. et al. (1998). Life-cycle inventory of biodiesel and petroleum diesel for use in an urban bus. A joint study sponsored by the US Department of Agriculture and the US Department of Energy. NREL, Final report, May 1998.
Sheehan et al. 1998b	Sheehan J., Camobreco V., Duffield J., Graboski M. & Shapouri H. (1998). An overview of biodiesel and petroleum diesel life-cycles. A joint study sponsored by the US Department of Agriculture and the US Department of Energy. NREL, May 1998.
Soya.be 2006	Soya.be (2006). Information about soy and soya products: Soybean oil production. Retrieved on the website of Soya.be on 12.05.2006, at: www.soya.be.
Tapasvi et al. 2004	Tapasvi D., Wiesenborn D. & Gustafson S. (2003). Process modelling approach for evaluating the economic feasibility of biodiesel production. Written for presentation at the 2004 North Central ASAE/CSAE Conference Sponsored by the Manitoba Section of CSAE Winnipeg, Canada, September 24-25, 2004.
UFOP 2004	UFOP (2004). Biodiesel flower power: Facts, arguments, tips. Published by the Union zur Förderung von Oel- und Proteinpflanzen e. V. (UFOP), Berlin. Eds: Bockey D., WPR Communication GmbH & Co. KG, Königswinter & Berlin.
UFOP 2006	UFOP (2006). Current situation and prospects for biodiesel and vegetable oils as fuels: From niche products to market players. By Dieter Bockey, Union for the Promotion of Oil and Protein Plants (UFOP), Version 02/2006.
United Soybean Board 2002	United Soybean Board (2002). US Soy Statistics. Retrieved on the website of the Unites Soybean Board on 13.05.2006, at: http://www.unitedsoybean.org/.
US Bureau of Census 2002	US Bureau of Census (2002). Oil mill Statistics. In: The Trade News Service, Vol. 88 (52), p. 17, December 27, 2002.

USMEF 2003	Hays K., US Meat Export Federation (2003). Soybean production in Brazil.
VIEWLS 2005	VIEWLS (2005). Shift gear to biofuels, Results and recommendations from the VIEWLS project (Clear Views on Clean Fuels). European Commission (NNE5-2001-00619), November 2005.
Woods & Bauen 2003	Woods J. & Bauen A. (2003). Technology status review and carbon abatement potential of renewable transport fuels in the UK. Prepared by Imperial College London Centre for Energy Policy and Technology (ICCEPT), for the Department of Trade and Industry / New and Renewable Energy Programme, 2003.
Wörgetter et al. 1999	Wörgetter M., Lechner M., Rathbauer J. (1999) Ecobalance biodiesel. Federal Institute of Agricultural Engineering, on order of the Federal Ministry for Agriculture and Forestry, Wieselburg.
Yusof & Chan 2004	Yusof B. & Chan K.W. (2004). The oil palm and its sustainability. In: Journal of Palm Oil Research, Vol. 16 (1), pp.1-10, June 2004. © Malaysian Palm Oil Board.
Yusof & Choo 2004	Yusof B. & Choo Y.M (2004). Crude palm oil as a source of biofuel: Its impact on price stabilization and environment. Malaysian Palm Oil Board (MPOB).
Zah & Hischier 2004	Zah R. and Hischier R. (2004) Life Cycle Inventories of Detergents. Final report ecoinvent 2000 No. 12. EMPA St. Gallen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Zhang et al. 2003a	Zhang Y., Dubé M.A., McLean D.D., Kates M. (2003). Biodiesel production from waste cooking oil: 1. Process design and technological assessment. In Bioresources Technology No. 89, pp. 1-16, Elsevier.
Zhang et al. 2003b	Zhang Y., Dubé M.A., McLean D.D., Kates M. (2003). Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. In Bioresources Technology No. 90, pp. 229-240, Elsevier.
Zilio 2005	Zilio J. (2005). Biodiesel economics in Brazil. Bunge Alimentos. In: Biofuels seminar, São Paulo, Brazil, May 20, 2005. Brazil-Germany chamber.

18 Synthetic biofuels

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Summary

The present chapter deals with the life cycle inventory of synthetic biofuels, including BTL (biomass-to-liquids) fuels and related processes. The expression ‘BTL fuels' here refers to biomass-based fuels (for use in the transportation sector) derived from the processing of syngas, itself obtained from the gasification of wood. Gasification is an energy process producing a gas (termed 'producer gas' or 'synthesis gas' or more commonly 'syngas') that can substitute fossil fuels in power generation, heat and/or combined heat and power application, or can be used for the production of liquid fuels and chemicals. Syngas indeed is a universal intermediate to a broad range of synthetic transportation liquid fuels (e.g. Fischer-Tropsch diesel, gasoline, naphtha, kerosene, methanol, ethanol, hydrogen, dimethyl ether, etc.) as well as gaseous fuels (methane from syngas). Within this report, the focus is put on (1) the gasification of wood and on the production of methanol from the resulting syngas and (2) on the production of methane (96% vol.) from syngas by methanation.

18.1 Introduction

Miscellaneous technologies are under development for converting biomass to energy, chemicals and/or transportation fuels. Examples are biochemical conversion (e.g. fermentation of agricultural crops and/or residues to ethanol) and chemical conversion (e.g. esterification of vegetable oils to methyl ester) or combinations thereof, at mild temperatures and pressures. Other examples are chemical conversion at elevated temperatures and/or pressures, such as hydrothermal upgrading or flash pyrolysis of agricultural residues or wood. Yet another technology is thermochemical conversion via synthesis gas (or syngas) as an intermediate product, which is the object of the present chapter.

The thermochemical conversion of biomass into transportation fuels and chemicals via syngas as an intermediate product, has two attractive features: (1) a very broad range of biomass feedstocks can be completely converted, and (2) syngas is a universal intermediate to a broad range of synthetic transportation fuels (e.g. Fischer-Tropsch diesel, gasoline, naphtha, kerosene, methanol, ethanol, hydrogen, dimethyl ether, etc.) and commodity/specialty chemicals (e.g. ammonia, methanol, fertilizers, detergent feedstock, synthetic base oils and specialty paraffinic waxes). The present chapter focuses attention on the conversion of biomass into syngas of a quality that is suitable for subsequent catalytic conversion, in particular, methanol synthesis.

This chapter documents the life cycle inventories for synthetic biofuel systems contained in the ecoinvent database. The related processes covered in the ecoinvent database are summarized in Tab. 18.1.

Tab. 18.1 Overview of the synthetic biofuels' unit processes covered in the ecoinvent database.

Name	Location	Category	SubCategory	unit
Synthetic biofuels				
waste wood chips, mixed, from industry, u=40%, at plant	CH	wood energy	fuels	m3
synthetic gas plant	CH	biomass	fuels	unit
synthetic gas, from wood, at fixed bed gasifier	CH	biomass	fuels	Nm3
synthetic gas, from wood, at fluidized bed gasifier	CH	biomass	fuels	Nm3
synthetic gas, production mix, at plant	CH	biomass	fuels	Nm3
methanol, from synthetic gas, at plant	CH	biomass	fuels	kg
methanol, from biomass, at regional storage	CH	biomass	fuels	kg
methane, 96 vol.-%, from synthetic gas, wood, at plant	CH	biomass	fuels	Nm3

The documentation is structured as follows:

- Section 17.2 (Raw material resources) provides some general information on the availability of feedstocks for gasification purposes in Switzerland.
- Section 18.3 (Wood chips) describes the datasets relating to wood chips covered in the present chapter (incl. composition and properties, applications and uses, system definition and life cycle inventory).
- Section 18.4 (Syngas from wood) describes the datasets relating to the gasification of wood chips to syngas covered in the present chapter (incl. composition and properties, applications and uses, system definition and life cycle inventory).
- Section 18.5 (Biomethanol from syngas) describes the datasets relating to the synthesis of methanol from syngas covered in the present chapter (incl. composition and properties, applications and uses, system definition and life cycle inventory).
- Section 18.6 (Methane 96% vol. from syngas) describes the datasets relating to the methanation of syngas to methane covered in the present chapter (incl. composition and properties, applications and uses, system definition and life cycle inventory).
- Section 18.7 (Data Quality Considerations) discusses the data quality indicators for the inventory of all the processes included in the present chapter.
- Section 18.8 (Cumulative Results and Interpretation) presents and discusses LCI results and values for the cumulative energy demand of selected processes in the chapter. These results are compared to similar results published in related articles and reports.
- Section 18.9 finally gives the conclusions.

18.2 Resources of Raw Materials

The present section discusses the resources for biomass gasification in Switzerland. The feedstocks for gasification and the subsequent conversion to methanol are here limited to forest and waste wood, which offers one of the largest potential in the country and has the advantage over other types of lignocellulosic biomass (e.g. fresh grass, straw) and wastes (e.g. black liquor from paper industry) to be more stable and more largely available. One should bear in mind though that gasification is in competition with several other uses of wood (e.g. heating, construction, paper, specialty chemicals and possibly ethanol production, power generation, etc.). The figures presented here are a potential and only a potential.

In Switzerland, biomass contributes 47.3 PJ or 5.1% of the total final energy consumption of 873 PJ (see Tab. 18.2). The biomass potential allows an increase by nearly 100%, which is the aim of the Swiss energy policy.

Tab. 18.2 Consumption and potential of wood and other biomass as energy sources. Adapted from (Bühler 2004).

	2003			Potential (medium-term)		
	Mm^3	PJ	%	Mm^3	PJ	%
Forestry wood	1.3	11.2	1.3%	3.2	27.6	3.2%
Wood residues from industry	1.1	9.5	1.1%	1.1	9.5	1.1%
Urban waste wood and demolition wood	0.2	1.7	0.2%	0.7	6.0	0.7%
Total wood	2.6	22.5	2.6%	5.0	43.1	4.9%
Other biomass	-	24.8	2.8%	-	35.0	4.0%
Total biomass	-	47.3	5.4%	-	78.1	8.9%
Total final energy	**-**	**873.0**	**100.0%**	**-**	**873.0**	**100.0%**

The main source of bioenergy in Switzerland is wood. In 2003, it contributed to 22.5 PJ or 2.6% of the total final energy consumption of the country. The major share of energy wood is used in boilers and stoves for household heating. Furthermore, automatic furnaces fuelled with wood residues and forestry wood chips are widely used in the industry and in district heating respectively. A few plants allow the combustion of urban waste and demolition wood and are equipped with adequate technologies (Bühler 2004).

All other biomass contributes 24.8 PJ (or 2.8%) to the final energy consumption and includes biomass contained in municipal solid waste, sewage sludge, paper sludge, agricultural residues and organic residues for the production of biogas (mostly used for heat and/or electricity production and as a vehicle fuel).

The present chapter envisages the conversion of wood to energy through the gasification process, and the subsequent production of methanol from the bio-synthesis gas (or bio-syngas). The potential of wood is therefore expressed in terms of syngas and methanol production. Two different types of technology are considered for gasification, namely fixed bed gasification (small-to-medium scale) and fluidized bed gasification (medium-to-large scale). The two technologies are largely discussed in section 18.4). The potential of syngas and methanol is indicated for both types of gasification technologies in Tab. 18.3.

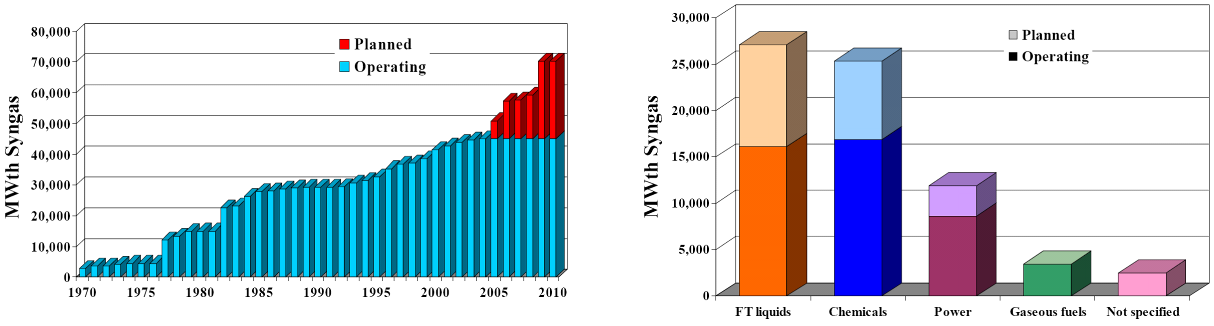
Tab. 18.3 Potential of syngas and methanol production from forest and waste wood.

	2003		Potential (medium-term)	
	kt	PJ	kt	PJ
Total wood	1'712.7	22.5	3'285.9	43.1
Syngas (through gasification)	-	19.1	-	36.6
Methanol	770.7	15.5	1'478.7	29.7

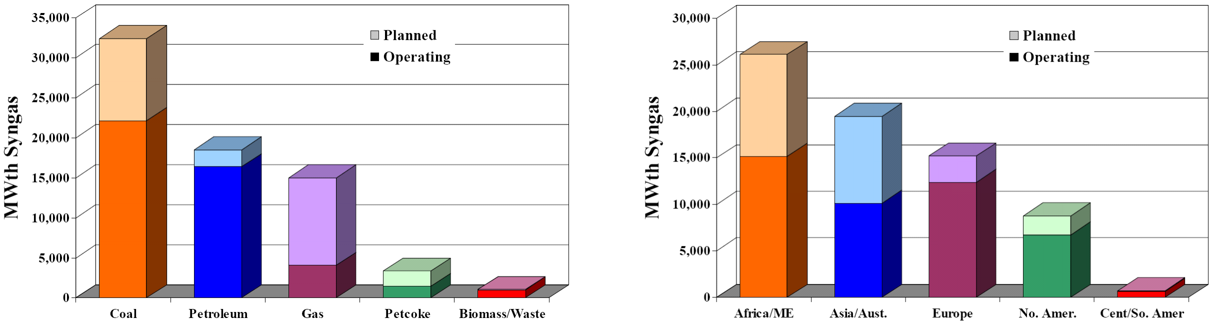
The figures indicated in Tab. 18.3 are only meant to give an idea of what could be the production of syngas and methanol in the medium term (i.e. 2010-2015) if all energy wood (i.e. “total wood” according to Tab. 18.2), as given in (Bühler 2004), were converted to these products. The present document does not evaluate a realistic potential of methanol or syngas in Switzerland. However, it indicates the size of a reasonable production plant (for each energy pathway) in the Swiss context. This topic is discussed further in section 18.4.

In principle, syngas (primarily consisting of CO and H_2) can be produced from any hydrocarbon feedstock, including: natural gas, naphtha, residual oil, petroleum coke, coal and biomass. The present chapter is concerned with the production of syngas from biomass. The lowest cost routes for syngas production, however, are based on natural gas, the cheapest option being remote or stranded reserves (NREL 2003). At present, syngas is most often used in place of natural gas to generate electricity, or as a basic raw material to produce chemicals and liquid fuels.

Within the past 30 years, the worldwide gasification production capacity has been growing at a fast and regular pace and is expected to keep progressing similarly or even faster. Most gasification plants today operate on coal or petroleum and are dedicated to the production of Fischer-Tropsch liquids, chemicals and, to a lesser extent, electricity (see Fig. 18.1). Although the gasification of biomass today remains very marginal (only a few percent of the total operating capacity according to the bottom-left diagram on Fig. 18.1), it has been gaining more and more interest in the past few years (as shown by the increasing number of pilot and demonstration projects and publications in the field).


Worldwide gasification capacity and growth

Gasification by product


Gasification by feedstock

Gasification by region

Fig. 18.1 The world gasification picture (NETL 2004).

The success of gasification technologies has been proven in applications worldwide, with production of over 40’000 MW_{th} of syngas in 2000. Successful commercial facilities have used “first generation” gasification technologies for over 20 years for products ranging from chemicals to fuels to electricity. Meeting the needs of new markets, however, will require a new generation of gasification technologies with advances in economics and efficiency.

Today, the majority of existing applications have been geared towards the production of a single product or a constant ratio of two or more products per facility. In the near future, with deregulation and rapidly changing market demands, the potential of gasification in expanding markets is in the use of low-cost and blended feedstocks and multi-product flexibility (NETL 2004).

Biomass gasification gives rise to significant research and development and is so far limited to demonstration-scale installations, most projects being oriented towards power generation. The processes characterised in the present chapter are situated at the horizon 2010 and take into account expected short term technological development.

18.3 Wood chips

18.3.1 Characterisation of wood chips

The feedstocks considered for syngas and methanol production in this chapter are limited to wood chips, comprised of both uncontaminated forest wood and waste demolition wood. Many energy wood processes have already been characterised in the ecoinvent database, and are directly available for consideration in the present chapter. A novel process considered here is the provision of waste wood chips, from the industry, including urban waste wood and demolition wood. The distribution of waste wood between hard and soft wood is considered to match the distribution considered within mixed forest woods, i.e. 28% hard woods and 72% soft woods (Werner 2003), in accordance with the FAO statistics of the wood industry in Switzerland. The composition and main characteristics of "clean" and waste wood chips are indicated in Tab. 18.4).

Tab. 18.4 Main characteristics and properties of hard, soft and mixed forest and waste wood.

		Wood chips, mixed, u=120%, at forest	**Wood chips, mixed, from industry, u=40%, at plant**	**Waste wood chips, mixed, from industry, u=40%, at plant**
basic unit in database		**m^3**	**m^3**	**m^3**
Types of wood included	-	72% soft wood chips and 28% of hard wood chips	72% soft wood chips and 28% of hard wood chips	72% soft wood chips and 28% of hard wood chips
Market share	%	64%	22%	14%
Moisture mass to dry mass ratio (u)	% wt.	120%	40%	40%
Moisture mass to total mass ratio	% wt.	54.5%	28.6%	28.6%
Bulk density of dry mass	kg/m^3_{dry}	188.6	188.6	188.6
Apparent density	kg/m^3_{fresh}	414.9	264.0	264.0
Lower heating value of dry volume	MJ/m^3_{dry}	3'294	3'465	3'640
Lower heating value of dry mass	MJ/kg_{dry}	18.9	18.9	19.8
Typical size of wood chips	mm x mm x mm	70 x 70 x 70	70 x 70 x 70	70 x 70 x 70
Oxygen	kg/kg	0.494	0.494	0.438
Carbon, fossil	kg/kg	0.000	0.000	0.000
Carbon, biogen	kg/kg	0.441	0.441	0.443
Hydrogen	kg/kg	0.061	0.061	0.057
Arsenic	ppm			4.1
Cadmium	ppm			3.4
Chloride	ppm			849
Chromium	ppm			32
Copper	ppm			27
Fluoride	ppm			42
Lead	ppm			314
Mercury	ppm			0.3
Nickel	ppm			6
Nitrogen	ppm			7'900
Phosphorous	ppm			200
Selenium	ppm			6
Zinc	ppm			535
Calcium	ppm			15'000
Aluminium	ppm			840
Iron	ppm			2'100
Potassium	ppm			890
Magnesium	ppm			1'060
Silicon	ppm			750
Sulphur	ppm			1'385
CO_2 Factor	kg/kg_{dry}	1.62	1.62	1.62
Formula		C10H14O7	C10H14O7	
CAS				
Source		*Bauer 2003*	*Bauer 2003*	*Reichenbach de Sousa 2001*

In general terms, waste wood will show a lower moisture content although the same is here considered for both forest and waste wood, i.e. about 30% (u=40%). Compared to uncontaminated forest wood, waste wood shows a slightly higher LHV and higher levels of heavy metals (due to the presence of paints and other contaminants) and plastics.

18.3.2 Applications and use of wood chips

Wood chips may be used in many applications. The applications of wood chips for energy purposes are covered in details in ecoinvent reports No. 6 (Bauer et al. 2003) and No. 9 (Werner et al. 2003). In the present chapter, wood chips are used for the production of syngas through gasification.

18.3.3 System definition

Waste wood chips are produced from waste demolition wood on the one hand and waste urban wood on the other hand. Whatever building demolition waste wood should be obtained from, the demolition or dismantling is in principle taken into account in the building process itself. Therefore, a process such as 'building, hall, wood construction' indicates: "*Includes the most important materials used and their disposal, the transportation of the parts to the building site and to the final disposal at the end of life. Also included is the requirement of electricity for construction, maintenance and demolition. Operation is not included.*". According to the way waste wood is disposed of, various processes may be selected such as 'disposal, building, waste wood, untreated, to final disposal', 'disposal, wood untreated, 20% water, to sanitary landfill', 'disposal, building wood, chrome preserved, 20% water, to municipal incineration', etc. In the present case, waste wood would be collected on the demolition site, and then transported to a wood processing facility for crushing. From there, wood chips are delivered to the gasification plant. The detailed supply chain of wood chips (including wood chips from forest, from industry and waste wood chips) is illustrated on Fig. 18.2.

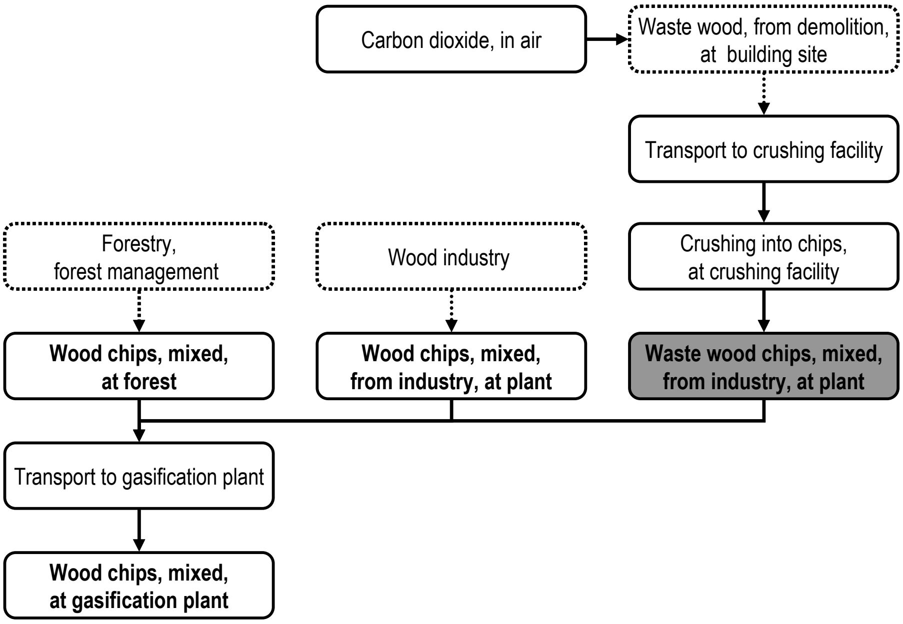


Fig. 18.2 Production of waste wood chips from demolition wood and supply of wood chips to gasification plant.

18.3.4 LCI of 'Waste wood chips, mixed, from industry, u=40%, at plant

It is assumed here that raw demolition waste wood is a neutral product with zero economic value and no associated impact. Such waste wood however, benefits from both the CO_2 credit 'Carbon dioxide in air', as its carbon has not been released yet. The gross calorific value of the biomass is not included, as it has been accounted for in the first place for the primary use of the wood. According to the specifications of biomass indicated in Tab. 18.4, the credit is as follows:

- Carbon dioxide, in air: 342 kg CO_2/m^3

This process includes transport of waste urban and demolition wood to a chopping facility and chopping of the wood into chips. The distance between the demolition site to the chopping facility is taken as 50 km, in agreement with hypotheses for other wood chips processes in the ecoinvent database. It is considered that the wood is not subject to any particular treatment prior to its subsequent use. Transport to the chopping facility is performed by 28t trucks. Chopping is done by a stationary electric chopper. In accordance with other processes in the ecoinvent database, the nature of the wood reflects the Swiss average wood consumption, i.e. 72% softwood (dried matter content = 169 kg/m^3 dried matter and lower heating value = 3’331 MJ/m^3) and 28% hardwood (dried matter content = 239 kg/m^3 dried matter and lower heating value = 4’436 MJ/m^3). The overall quality of waste wood chips is therefore:

- dried matter content: 188.6 kg/m^3 dried matter (u=0%)
- lower heating value: 3’640 MJ/m^3.

As indicated above, the CO_2 credit 'Carbon dioxide in air' is taken as 342 kg CO_2 per m^3 of waste wood chips. The composition of waste wood is indicated in Tab. 18.4. The unit process raw data of ‘waste wood chips, mixed, from industry, u=40%, at plant’ is indicated in Tab. 18.5.

Other inputs and outputs such as infrastructure, tap water, wood wastes from sorting, and effluents are taken from (Jungbluth et al. 2002), based on data from a producer of waste wood chips in CH.

Tab. 18.5 Unit process raw data of the datasets ‘waste wood chips, from industry, u=40%, at plant’.

	Name	Location	InfrastructureProcess	Unit	waste wood chips, mixed, from industry, u=40%, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				m3			
product	waste wood chips, mixed, from industry, u=40%, at plant	CH	0	m3	1.00E+0			
resource, in air	Carbon dioxide, in air	-	-	kg	3.42E+2	1	1.30	(1,5,1,1,3,na); Calculated from composition of wood
technosphere	Industrial residual wood chopping, stationary electric chopper, at plant	RER	0	kg	1.89E+2	1	1.32	(3,5,1,2,3,na); Expert estimate
	transport, lorry 28t	CH	0	tkm	1.32E+1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	sawmill	RER	1	unit	7.80E-9	1	3.06	
	tap water, at user	CH	0	kg	8.22E+0	1	1.24	(1,4,2,1,1,5); Based on the data from a producer of waste wood chips in CH.
	disposal, building wood, chrome preserved, 20% water, to municipal	CH	0	kg	2.83E-1	1	1.24	
	treatment, particle board production effluent, to wastewater treatment,	CH	0	m3	8.22E-3	1	1.24	

18.4 Syngas from wood

18.4.1 Characterisation of syngas

The characteristics of syngas are very much dependent on the technology considered, and the post-gasification treatment steps, which themselves depend very much on the use of the gas downstream of the gasification. Syngas for power generation, indeed, will not require the same properties (i.e. heating value, composition, purity, etc.) as syngas meant for methanol, dimethyl ether or yet Fischer-Tropsch (FT) diesel production. Therefore, in order to keep syngas production as independent as possible from its subsequent use, the limits of the gasification plant are set as close to the gasifier as possible, i.e. excluding most post-gasification treatment stages. The limits of the system considered for the gasification process are indicated in Fig. 18.3.

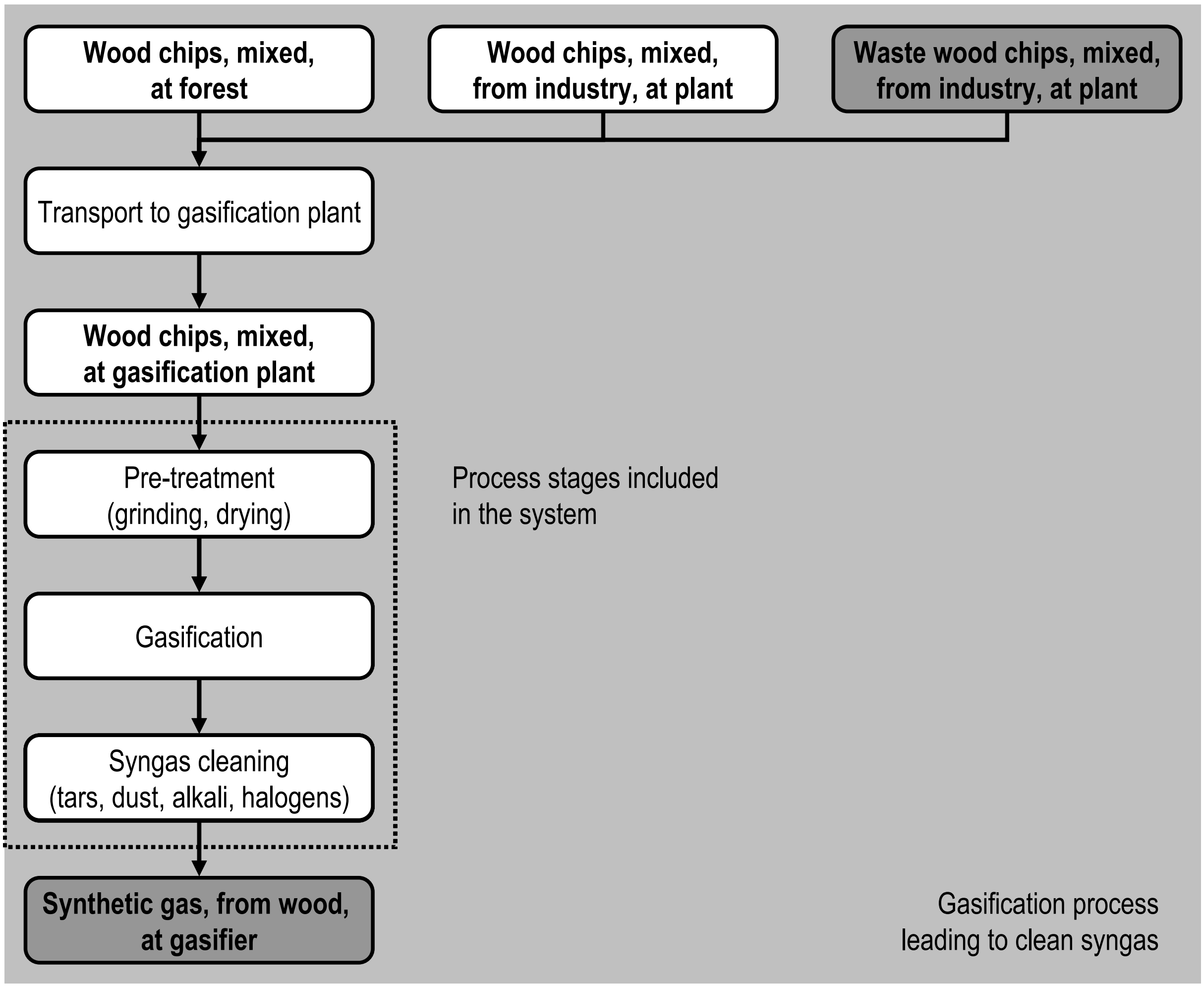


Fig. 18.3 Limits of the gasification process.

Therefore, the two processes 'synthetic gas, from wood, at fixed bed gasifier' and 'synthetic gas, from wood, at fluidized bed gasifier' characterise the synthetic gas resulting from the gasification stage after the cleaning process which consists in the removal of tars, dust, alkali, BTX (benzene, toluene and xylenes) and halogens. The various stages of the cleaning process are described in detail in paragraph 18.4.3. Although some of the cleaning stages may somehow be dependent on the subsequent use of the syngas (different levels of purity required), it is not possible to dissociate these process stages from the gasification, as some of the equipment are virtually part of the gasifier itself. The cleaning stages envisaged in the gasification process are suitable for subsequent methanol synthesis. Typical compositions and characteristics of clean syngas are presented in Tab. 18.6.

Tab. 18.6 Composition of syngas from biomass, through fixed bed and fluidized bed gasifiers.

basic unit in database		Synthetic gas from fixed bed gasifier Nm^3	Synthetic gas from fluidized bed gasifier Nm^3	Synthetic gas mix (50% fixed bed, 50% fluidized bed) Nm^3
Lower heating value (Hu)	MJ/kg	4.5	4.7	4.6
Lower heating value (Hu)	MJ/Nm^3	5.2	5.4	5.3
Density 20°C	kg/m^3	1.15	1.15	1.15
Oxygen	kg/kg	0.306	0.314	0.310
Carbon, fossil	kg/kg	0.000	0.000	0.000
Carbon, biogen	kg/kg	0.135	0.140	0.138
Hydrogen	kg/kg	0.026	0.021	0.023
Nitrogen	kg/kg	0.533	0.525	0.529
Wet composition				
N_2	%mol	47.6	50.4	49.0
H_2O	%mol	14.6	13.7	14.2
H_2	%mol	10.7	5.6	8.2
CO	%mol	15.3	14.0	14.7
CO_2	%mol	8.9	12.5	10.7
CH_4	%mol	2.2	3.1	2.7
C_nH_m	%mol	0.6	0.6	0.6
Dry N-free composition				
H_2	%mol	28.4	15.5	22.0
CO	%mol	40.5	39.2	39.9
CO_2	%mol	23.6	34.9	29.3
CH_4	%mol	5.9	8.7	7.3
C_nH_m	%mol	1.5	1.7	1.6
Wet composition				
N_2	%wt	53.3	52.5	52.9
H_2O	%wt	10.5	9.2	9.9
H_2	%wt	0.9	0.4	0.6
CO	%wt	17.1	14.6	15.9
CO_2	%wt	15.7	20.4	18.1
CH_4	%wt	1.4	1.8	1.6
C_nH_m	%wt	1.0	1.0	1.0
CO_2 Factor	kg/MJ (Hu)	0.1096	0.1096	0.1096
CO_2 Factor	kg/kg	0.50	0.51	0.51

The composition of syngas is dependent on a large number of factors, such as:

- the gasification technology: fixed or fluidized bed, atmospheric or pressurized reactor, oxygen-blown or air-blown, direct or indirect heating of the gasification reaction
- the choice of various operating parameters: steam-to-biomass (S/B) ratio, equivalence ratio[45] (E/R), temperature, pressure
- the sequence of cleaning processes downstream of the gasification reactor
- the composition of the feedstock (ultimate analysis, moisture content, etc.).

Some of the parameters mentioned above are often dictated by the subsequent use of syngas. As a result, the gasification of a given type of feedstock, in a given type of gasifier will result in different syngas compositions according to the choice of the various parameters. The reference case considered for fixed bed gasification on the one hand and fluidized bed gasification on the other hand are taken as neutral as possible, most representative of what is found in the literature, with an emphasis on the co-

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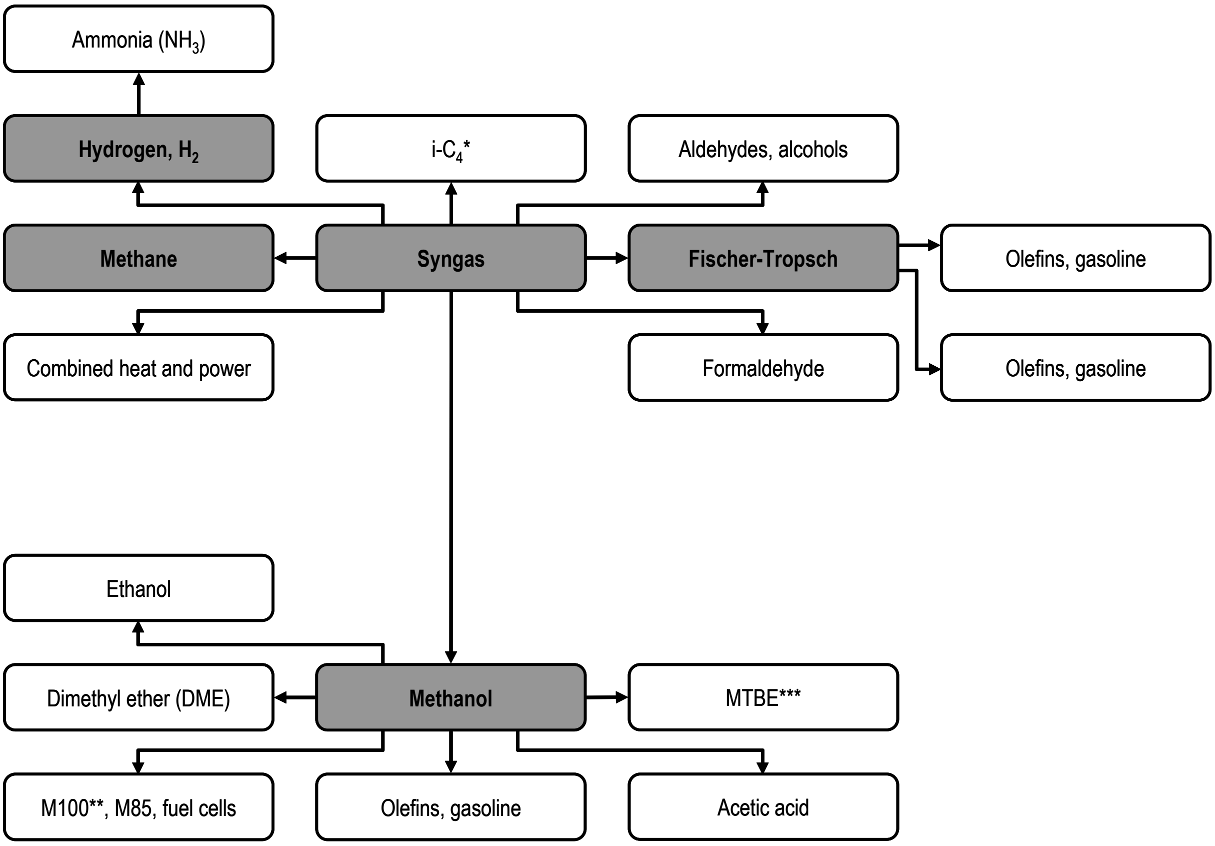
[45] E/R ratio: ratio of effective actual oxygen input to the theoretical stoechiometric oxygen input for the combustion reaction.

herence of the data. The choice of the technology and operating parameters is detailed and discussed in paragraph 18.4.3.

18.4.2 Applications and use of syngas

The processing of syngas can lead to a large number of products for various applications, as illustrated on Fig. 18.4.

The flow diagram on Fig. 18.4 replaces the production of methanol from syngas in the global system of syngas processing to synthetic liquid fuels (methanol, but also mixed alcohols, Fischer-Tropsch liquids, DME, gasoline, etc.), hydrogen (H_2), chemicals (formaldehyde, ammonia, acetic acid), combined heat and power (CHP) production, or yet synthetic natural gas through methanation (for injection into the natural gas network or use as a vehicle fuel).



* i-C4 refers to iso-synthetic fuels (i-C4 hydrocarbons).

** M100 refers to as pure methanol, while M85 refers to a mixture of 15% vol. gasoline with 85% vol. methanol. This terminology generally applies to methanol used as transportation fuels.

*** MTBE refers to methyl-tert-butyl-ether, resulting from the reaction of methanol with isobutene.

Fig. 18.4 Schematic diagram of synthetic fuels and chemicals production from syngas (NREL 2003).

History an international experience

Biomass gasification has a long development history. Numerous systems have been developed and commercialized in the past to supply thermal energy and fuel gas or synthesis gas (syngas) for industrial and transportation applications. Simple gasification systems are still available today that are suitable for developing countries where large quantities of easily accessible biomass are available. These systems are generally lower in efficiency and produce either heat or electrical power. In parallel, advanced systems are being developed by industrialised countries for power and combined heat/power generation, but also for the production of transportation fuels and chemicals. Such advanced systems could provide high efficiencies with reduced emissions to mitigate greenhouse gas emissions.

Gasification is the conversion of hydrocarbons (including natural gas, naphtha, residual oil, petroleum coke, coal, and biomass) into a combustible gas mixture by the partial oxidation of biomass at high temperatures, typically in the range 800-900°C. The low calorific value gas produced (approximately 4-6 MJ/Nm^3, see Tab. 18.6) may be burnt directly for heat and power production or used as a fuel for gas engines. The product gas, referred to as synthetic gas or syngas, can also be used as a feedstock for the production of liquid transportation fuels, chemicals and/or hydrogen.

In its simplest form, syngas is composed of two diatomic molecules, CO and H_2 that provide the building blocks upon which an entire field of fuel science and technology is based. Over the years, the gaseous mixture of CO and H_2 has had many names depending on how it was formed; producer gas, town gas, blue water gas, synthesis gas and syngas, to name only a few. In the 19th century, coal gasification was used to provide much of the syngas used for lighting and heating (NREL 2003). The beginning of the 20th century and the extensive availability of cheap liquid fuel saw the dawn of fuels and chemicals synthesis from syngas.

The synthesis of hydrocarbons from CO hydrogenation was discovered in 1902 by Sabatier and Sanderens who produced methane by passing CO and H_2 over Ni, Fe and Co catalysts. At about the same time, the first commercial hydrogen from syngas produced from steam methane reforming was commercialized. Haber and Bosch discovered the synthesis of ammonia from H_2 and N_2 in 1910 and the first industrial ammonia synthesis plant was commissioned in 1913. The production of liquid hydrocarbons and oxygenates from syngas conversion over iron catalysts was discovered in 1923 by Fischer and Tropsch. Variations on this synthesis pathway were soon to follow for the selective production of methanol, mixed alcohols, and isosynthesis products. Another outgrowth of Fischer-Tropsch (FT) synthesis was the hydroformylation of olefins discovered in 1938.

With the development of the petroleum industry in the 1940s and beyond, the unattractive economics of many of these syngas routes became an issue and were replaced by petroleum-based processes. Methanol and ammonia, however, continue to be produced from syngas using similar processes. Apart from hydrogen production, these processes constitute the major uses of syngas.

More recently, increasing environmental concerns and tighter regulations surrounding fossil fuel use also provided impetus for syngas conversion technologies to produce cleaner (virtually no sulphur) fuels and chemicals. The use of methanol and isobutene for the production of methyl tertiary-butyl ether (MTBE), an octane enhancing oxygenated component in reformulated gasoline, also increased demand for syngas conversion technologies.

MTBE itself, however, is becoming an environmental concern as a watershed pollutant and the future use of this oxygenate is uncertain. The latest environmental driver to likely increase demand for syngas even more is the goal of establishing a hydrogen economy. The vision is that hydrogen will be the fuel of choice for transportation and electricity generation via high efficiency, environmentally benign fuel cells. In principle, syngas can be produced from any hydrocarbon feedstock. These include natural gas, naphtha, residual oil, petroleum coke, coal, and biomass, the lowest cost route being currently based on natural gas. Recently, however, with growing environmental concerns, the use of biomass for syngas production through gasification has been receiving more and more attention, and although it has not yet reached commercial scale, it is considered a very promising route for bioenergy.

Gasification experience in Switzerland

In Switzerland, so far, gasification experience has been limited to research and development and to two pilot-demonstration plants, the Pyroforce gasifier and the Xylowatt gasifier (Bühler 2004). These experiences are discussed below.

The Pyroforce unit consists in a 200 kW_e gasifier combined with a Jenbacher engine at a military research centre at Spiez, near Interlaken. The plant employs a Pyroforce gasifier, based on the KDH (Kloeckner Humbolt Deutz) high temperature gasification process and a dry gas clean-up system. The downdraft fixed bed gasifier maintains a temperature of 1200-1300°C in the combustion zone. Operation experience can be summarized as follows:

- Plant commissioning from autumn 2000 to March 2001
- Several test runs in 2001, some difficulties and failures
- Improvement of some parts, new start in 2002
- The plant runs more or less continuously from Monday to Friday each week at partial load of 100 kW with only minor problems. Each week a detailed report of the operating experience is available.
- Operating hours (total system with engine) until April 2005: more than 5'000 hours

Although pilot tests were conducted with demolition wood, uncontaminated wood chips will be used as the gasification feed material.

The Xylowatt unit, a 60 kW_e gasifier, is based on the Indian Institute of Science (IISc) technology. It is an air suction low pressure, open top co-current downdraft moving bed system, with a specially designed lateral air inlet to reduce tar production. A pilot demonstration plant designed for 130 kW_{th} and 55 kW_e capacity is in operation in the sawmill Despond in Bulle (FR). The gasification feed material is uncontaminated woody biomass. In March 2004, total engine hours were adding up to 1'940. The plant consists of:

- a reactor of gasification (incl. wood silo, screws, ash extraction)
- gas treatment devices (incl. cyclone, heat exchanger, scrubbers, filter and blower)
- condensate treatment devices (incl. decanter, flocculation, cooling system and pumps)
- a naturally aspirated gas engine and generator.

18.4.3 System definition

As already exposed earlier, the wood chips supplied to the gasification plant will consist of a mixture of wood chips from forest management, wood chips from the wood industry and wood chips from waste demolition and urban wood. The respective shares of each feedstock are here defined in accordance with the data presented in Tab. 18.2, resulting in the following data:

- wood chips, mixed, u=120%, at forest: 64% (corresponding to 3.2/5)
- wood chips, mixed, from industry, u=40%, at plant: 22% (corresponding to 1.1/5)
- waste wood chips, mixed, from industry, u=40%, at plant: 14% (corresponding to 0.7/5)

Quantitative data of the fixed bed and fluidized bed gasification processes are detailed in paragraphs 18.4.6 and 18.4.7 respectively.

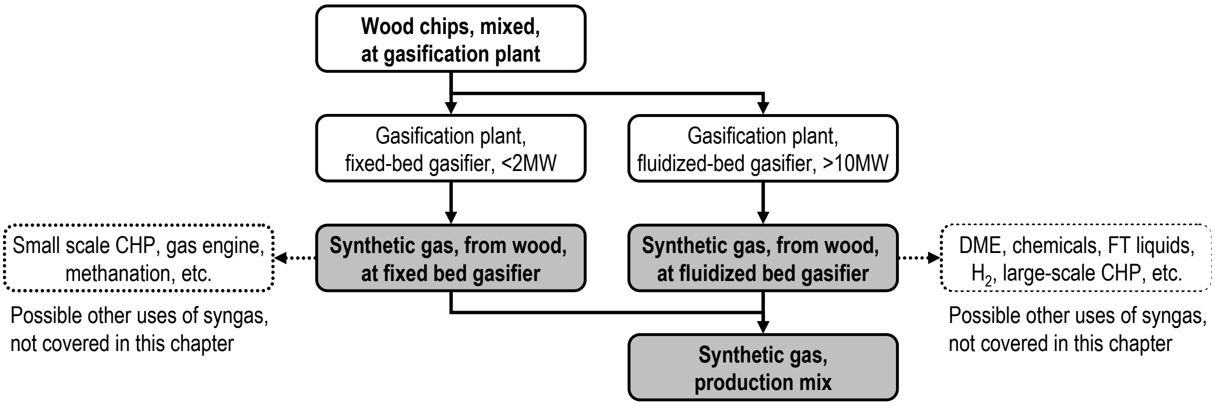


Fig. 18.5 Limits of the gasification processes covered in this chapter.

Wood chips conditioning

The first step of the gasification consists in conditioning the feedstock according to the appropriate requirements of the gasification process. These requirements apply to both the size and the water content of the chips. The maximum size is particularly dependent on the technology, fluidized bed being much more flexible in terms of quality and size. On average, it is estimated that wood chips should pass a 30 mm sieve. The electricity requirements for crushing/grinding the large wood chips down to smaller 30x30x30 mm chips is of the order of 5-10 kWh per t of fresh chips (Hamelinck 2001).

The moisture of each lot of wood chips (see paragraph 18.3.1) is expressed as ratio of the weight of water to the weight of the dry mater (u). The corresponding water contents (in percentage weight of the total mass) are equal to 55%, 28% and 28%, for wood chips at forest, wood chips from industry and waste wood chips from industry respectively. According to the technical requirements of the gasification process, the moisture content should be brought down to 10-15% (Tijmensen 2002), i.e. u=15%. According to the literature and given the initial moisture of the chips, the heat and electricity requirements for bringing the water content down to 10-15% are respectively 2.8 MJ and 0.025 kWh per kg of evaporated water. In this study, the heat is considered to be supplied by waste heat from the gasification process.

Gasification technology

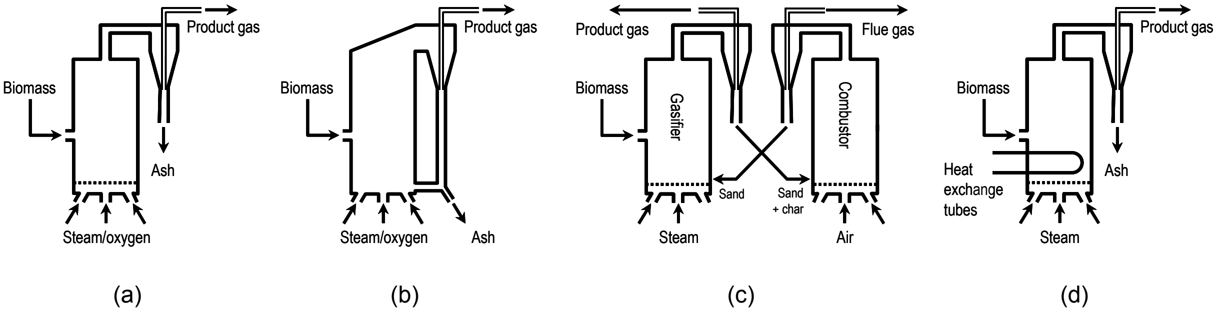
Gasifiers convert biomass into syngas by heating it to above 700°C in an oxygen poor environment. This principally comprises H_2 and CO, the feed gases required for methanol synthesis. The syngas is then cooled and quenched with a water spray to remove particulates, and cleaned up to remove sulphur compounds as well as other contaminants.

Gasifiers have been investigated for more than a century, and many different types have been developed. Gasifiers are basically of two main types, namely fixed bed and fluidized bed (FB) gasifiers, with variations within each type. A third type, the entrained-flow (EF) gasifier, has been developed for coal gasification, but the need for a finely divided feed material (<0.1-0.4mm) represents a major challenge for fibrous materials like woody biomass and makes the process highly unsuitable for most biomass materials. This type of gasifier is therefore no longer discussed in the present chapter.

Fixed bed gasifiers have been the traditional technology for gasification, operated at temperatures around 1000°C. Depending on the direction of air flow, the gasifiers are classified as downdraft (also often referred to as co-current), updraft (also termed counter-current) or cross-flow. Downdraft fixed bed gasifiers are limited in scale and require a well-defined fuel, making them not fuel-flexible. Updraft fixed bed gasifiers can be scaled up, however, they produce a product gas with very high tar concentrations. This tar should be removed for the major part from the gas, creating a gas-cleaning problem.

Fluidized bed (FB) gasification has been used extensively for coal gasification for many years, its advantage over fixed bed gasifiers being the uniform temperature distribution achieved in the gasification zone. The uniformity of temperature is achieved by using a bed of fine-grained material into which air is introduced, thereby fluidising the bed material and ensuring an intimate mixing of the combustion gas and the bed material. Compared to downdraft gasifiers, FB gasifiers are relatively fuel-flexible considering size and biomass composition, but there are serious remaining limitations to the fuels that are acceptable. These limitations are imposed by the fact that FB gasifiers use solid bed material (e.g. sand) as fluidisation material and heat carrier. This is an intrinsically weak point, as minerals in the biomass ash tend to react with the bed material forming melts and agglomerates that disturb the fluidisation. Frequent replacement of the bed material can prevent agglomeration. However, the consumption and disposal of spent bed material as chemical waste are significant economic cost drivers. Fluidized bed gasifiers are typically operated at 800-1000°C (limited by the melting properties of the bed material). For biomass, the carbon conversion is 90-98% (depending on the temperature and fuel). FB gasifiers can be operated at high pressures, the advantage being for those applications where the gas must be compressed downstream (e.g. gas turbine).

The two main types of FB gasifiers are circulating fluidized bed (CFB) and bubbling fluidized bed (BFB) gasifiers (see Fig. 18.6). CFB gasifiers are able to cope with high capacity throughputs and are used in the paper industry for the gasification of bark and other forestry residues. The bed material is circulated between the reactor and a cyclone separator, where the ash is removed and the bed material and char returned to the reactor. BFB gasifiers consist of a vessel with a grate at the bottom through which air is introduced. Above the grate is the moving bed of fine-grained material into which the biomass feed is introduced. Regulation of the temperature to 700-900°C is maintained by controlling the air/biomass ratio. The biomass is pyrolysed in the hot bed to form a char with gaseous compounds, the high molecular weight compounds being cracked by contact with the hot bed material.



Alternative designs for biomass gasification in fluidized bed reactors:
- (a) a bubbling fluidized bed
- (b) a circulating fluidized bed
- (c) an indirectly-heated gasifier (BCL type)
- (d) another indirectly-heated gasifier (MTCI type)

Fig. 18.6 Alternative designs for biomass gasification in fluidized bed reactors.

Regardless of the type of gasifier (fixed bed or fluidized bed), the most significant differences between gasifiers are whether they are pressurised or atmospheric, fed with air or with oxygen, and heated directly or indirectly. The advantages and disadvantages of each option are given below:

- Pressurised or atmospheric: Pressurised gasifiers are well suited to the co-generation of electricity. This is because the output gases from a pressurised gasifier are also pressurised, and are therefore suitable to supply a gas turbine. Pressurised gasifier systems also require smaller downstream equipment, which is less expensive. In contrast, the syngas produced from an atmospheric gasifier, must be compressed, which requires significant energy. Atmospheric gasifiers require larger downstream equipment than pressurised gasifier systems, but benefit from a large commercial experience.

- Air-blown or oxygen-blown: Air-blown plants are cheaper and simpler to operate than oxygen-blown plants, since no air/oxygen separation plant is required. However, they suffer from nitrogen-diluted syngas and therefore require larger downstream equipment. In oxygen-blown systems, oxygen is isolated in a cryogenic facility which makes oxygen-blown gasifiers more complex and expensive, but avoid these problems of nitrogen dilution and larger downstream equipment.
- Directly or indirectly heated: Directly heated gasifiers (also referred to as autothermal gasifiers) operate by partially oxidising their biomass, resulting in a limited combustion of the feedstock which powers the gasification reaction. These gasifiers produce less tar, therefore addressing one of the major problems associated with biomass gasification. Indirectly heated gasifiers (also referred to as allothermal gasifiers) require a heat exchanger and produce more tars. This study does not consider directly heated gasifiers in detail.

An extensive review of gasifier manufacturers in Europe, the US and Canada (Quaak et al. 2000) identified 50 manufacturers offering commercial gasification plants. The distribution of gasifiers according to the design and type of reactor was as follows: 75% were downdraft fixed bed gasifiers, 20% were fluidized bed gasifiers, 2.5% were updraft fixed bed gasifiers and 2.5% were of other designs. The comparison of the performance (in terms of efficiency, gas composition, etc.) of various designs of gasifiers is presented in paragraph 18.4.4.

The diagram on Fig. 18.7 indicates the typical range of feed capacity applications for the various types of gasifier designs. On a general basis, fixed bed are more appropriate for low capacity (<10MW$_{th}$), whereas fluidized bed gasifiers are more adapted to larger capacities (>10 MW$_{th}$).

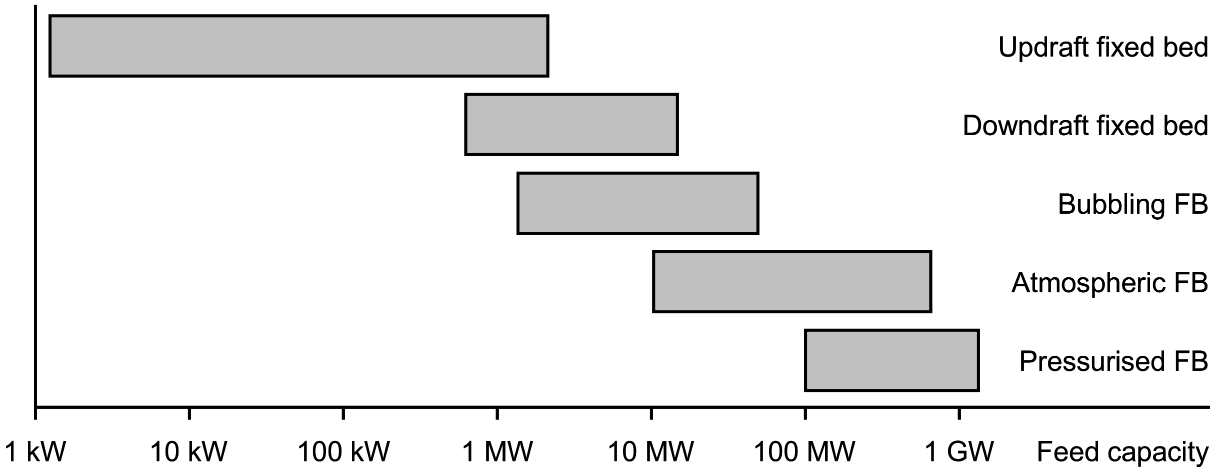


Fig. 18.7 Ranges of typical feed capacity of various types of gasifiers.

These variety of gasification designs lead to a wide range of syngas composition, with H_2:CO ratios varying between 0.45 to 2 (Tijmensen 2002). Any raw-biomass-derived syngas contains contaminants such as H_2S, HCl, NH_3, HCN, COS, dust and alkalis. Consequently, the syngas needs to be cleaned to make it suitable for subsequent processing.

Syngas Cleaning

Although predominantly CO and H_2, syngas also contains many other products, notably particulates, condensable tars, alkali compounds, H_2S, HCl, NH_3, HCN and COS. These potential contaminants need to be removed to prevent poisoning of the catalysts that are a key to almost all existing downstream processes including methanol synthesis.

Ash particles (dust) cause wear and corrosion throughout the plant. Particulate concentrations in raw syngas from most fluidized gasifiers will generally be of the order of 5000 ppm (wt.) and should be brought down to as low as 10 ppm (wt.). If tars are spontaneously cracked in high pressure gasifiers, they can be produced through atmospheric gasification. Below 500°C, tars condense on particulates and equipment, which leads to corrosion and sticking. Gas phase alkali metal compounds contribute to fouling, slagging, corrosion, and agglomeration problems in energy conversion facilities. At temperatures in excess of about 600°C these metals will remain in the vapour phase and their concentrations will by far exceed maximum tolerance of downstream catalysts. Sulphur, present as H_2S and COS, poisons catalysts by chemically bonding to active sites. Cleaning requirements for methanol synthesis are 0.10-0.25 ppm (van Dijk 1995; Katofsky 1993). On a general basis, the tolerance of the various catalysts for contaminants is low and 'deep' cleaning is required.

The gas can be cleaned using available conventional technology, by applying gas cooling, low temperature filtration, and water scrubbing at 100-250 °C. Alternatively, hot gas cleaning can be considered, using ceramic filters and reagents at 350-800 °C. The considered pressure range is no problem for either of the technologies. Hot gas cleaning is advantageous for the overall energy balance when a reformer or a ceramic membrane is applied directly after the cleaning section, because these processes require a high inlet temperature. However, not all elements of hot gas cleaning are yet proven technology, while there is little uncertainty about the cleaning effectiveness of low temperature gas cleaning (Tijmensen 2002; Hamelinck 2001). Tar cracking (indicated as optional) is required after atmospheric gasification. Both cleaning concepts are depicted in Fig. 18.8.

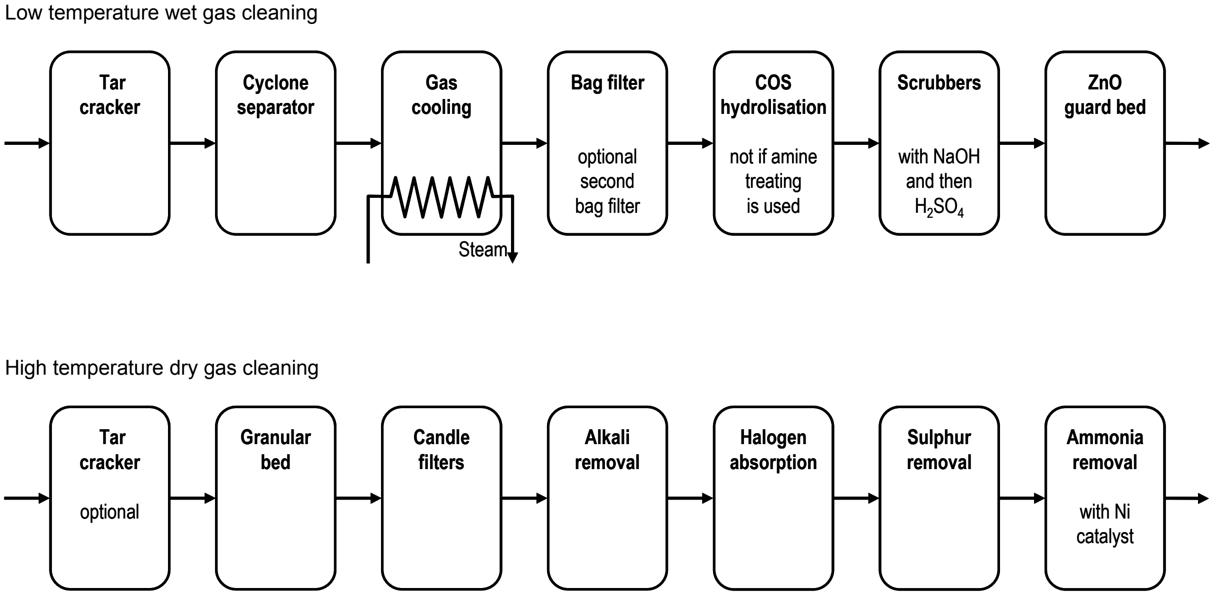


Fig. 18.8 Conventional low temperature wet cleaning and advanced high temperature dry cleaning (Hamelinck 2003).

In low temperature wet cleaning, a tar cracker containing dolomite is required downstream of atmospheric gasifiers. The cracked tars are recycled to the gasifier. It is not yet clear today to what extent tars are removed (Tijmensen 2002). A cyclone separator removes most of the solid impurities, down to sizes of approximately 5 μm (Katofsky 1993). Before passing through a bag filter (where remaining particulates and alkali are removed, the gas is cooled to just above the water dew point, thereby producing process steam. After the filter unit, the syngas is scrubbed down to 40°C below the water dew point, by means of water. Residual particulates, vapour phase chemical species, reduced halogen gases and reduced nitrogen compounds are removed to a large extent. The scrubber usually consists of an alkaline part where the bulk of H_2S is removed with NaOH solution, and an acid part for ammonia/cyanide removal. By experience, it is admitted that below 30 ppm H_2S in the raw syngas, bulk sulphur removal is not necessary. A ZnO bed is sufficient to reduce the sulphur concentration to below 0.1 ppm. The ZnO serves one year and is not regenerated. The effectiveness of cold gas cleaning has been proven for coal gasification combined-cycle and FT synthesis applications (Hamelinck 2001).

Hot gas cleaning removes particles for about 99.8 % by granular beds and ceramic candle filters. Simultaneously SO_x and NO_x are removed by injection of sorbents. Alkali removal via physical adsorption or chemisorption can be implemented at 750-900 °C, although lead and zinc can not be removed at this temperature. Sulphur is further removed by chemisorption. Thereafter in absence of H_2S, 99.5% of the NH_3 can be decomposed over a nickel catalyst. Only HCN may be insufficiently removed by hot gas cleaning, leading to shorter catalyst life in downstream reactors. As a general rule, hot gas cleaning is only sensible if it is followed by hot process units like reforming or shifting. Hot gas cleaning is not applied after atmospheric gasification since the subsequent compression of the syngas necessitates cooling anyway.

Wet low temperature fuel gas cleaning is the preferred method on the short term (van Ree 1995). This method will have some energy penalty and requires additional wastewater treatment, but is more certain to be effective on the short-to-medium term than hot dry gas cleaning. In this study, in relation with the choice of atmospheric gasification, low temperature wet gas cleaning is preferred to high temperature dry gas cleaning.

Biomass gasification

Within the frame of the ecoinvent database, two gasification designs are characterised, one fixed bed option and one fluidized bed option. The choice of the design is based partly on the representativeness of the technology and its suitability to dealing with biomass feedstocks and appropriateness to the Swiss context. The two process designs selected for this report are defined in Tab. 18.7.

Tab. 18.7 Biomass gasification process designs in the ecoinvent database.

Process name	Fixed bed gasifier <2MW	Fluidized bed gasifier >10MW
Gasifier technology	Fixed bed	Fluidized bed
Feed capacity	1 MW (5 t/day)	200 MW (1'000 t/day)
Direct/indirect	Indirect	Indirect
Atmospheric/pressurised	Atmospheric	Atmospheric
Air-blown/oxygen/blown	Air-blown	Air-blown
Gas treatment design	Low temperature wet gas cleaning	Low temperature wet gas cleaning

The choice of these technologies somehow dictates the composition of the syngas exiting the gasification unit, and therefore also influences the choice of options for the subsequent methanol synthesis. On a general basis, the synthesis of methanol from biomass-based syngas does not differ much from that based on natural gas. The process of methanol production is now described.

18.4.4 Overall process performance (incl. methanol synthesis)

This paragraph aims at summarizing the performance of biomass gasification to syngas and methanol synthesis. The data presented in Tab. 18.8 and Tab. 18.9 is the result of an extensive literature survey. All references are indicated in the table, together with the most relevant indicators and parameters. As operating conditions and performance can be measured in many different ways, various indicators of the performance are indicated below:

Equivalence ratio (E/R): ratio of the actual mass flow of oxygen injected in the reactor in the form of air (resp. oxygen in the case of oxygen-blown gasifiers) to the mass flow of oxygen that would be required for the stoechiometric combustion of the fuel. Note that in the calculations, only the mass flow of the oxygen supplied by air or oxygen is considered, disregarding the oxygen input by steam in the case of steam/oxygen-blown directly heated gasifiers.

Steam-to-biomass ratio (S/B): ratio of the mass flow of steam entering the gasifier to the mass flow of dry matter in the biomass. In order to measure the use of steam in the gasification, the consumption is indeed often ‘indicated’ in the form of the steam ratio.

Cold gas efficiency (CGE): syngas yield (Nm^3/kg_{feed}) times the ratio of the heating value of syngas (MJ/Nm^3) to the heating value of the feed (MJ/kg). This indicator applies only to the gasification process and is most often reported in literature references.

$$\text{CGE} = \text{Syngas yield}\left(\text{Nm}^3/\text{kg}_{\text{fuel}}\right)\times\frac{\text{Energy content of syngas}\left(\text{MJ}/\text{Nm}^3\right)}{\text{Energy content of the feed}\left(\text{MJ}/\text{kg}\right)}$$

Mass conversion efficiency (MCE): ratio of the mass of methanol to the mass of dry biomass. This indicator applies only to the global wood-to-methanol process.

$$\text{MCE} = \frac{\text{Mass of methanol}\left(\text{kg}\right)}{\text{Mass of dry biomass}\left(\text{kg}\right)}$$

The literature survey presented in Tab. 18.8 and Tab. 18.9 is the result of the compilation and normalisation of experimental and modelling data reported in more than 20 literature references from 1993 to 2005, covering most gasifier designs and methanol production schemes. Although there are many parameters which can differ from one study to the other, thus making it extremely awkward to define a “typical” case, the data should however give a relatively good image of typical yields, gas compositions and performances of the process described in this chapter. In order to allow a comparison between the data, the composition is always given in terms of % mol. (equivalent to % vol.) of the nitrogen-free dry syngas. When available or when the data is sufficiently detailed to perform the calculations, the various performance indicators are reported.

The data is divided into the main types of gasifiers and designs, namely (1) fixed bed, (2) fluidized bed BTL design (see Fig. 18.6c), (3) pressurized fluidized bed and (4) atmospheric fluidized bed. In each case, a reference set of data is established based on average values. When data were found to deviate significantly from average values, they were excluded. These reference sets of data are indicated in bold characters at the end of each group. As indicated before (see Tab. 18.7), the gasifiers included in the ecoinvent database correspond to the fixed bed reference set, and the atmospheric fluidized bed reference set (shaded columns in Tab. 18.8 and Tab. 18.9).

Tab. 18.8 Summary of the performance of wood gasification to syngas and methanol synthesis (fixed bed, BCL and pressurized fluidized bed gasifiers).

Operating conditions / Performance	Unit	Rao 2004	Hanaoka 2003		Giordano 1998	OPET 2002	**Ref.**	ICCEPT 2003	Rollins 2002	Babu 2002	Hamelinck 2001	Williams 1995	**Ref.**	Rapaccini 1999	Rollins 2002		Hamelinck 2001		Williams 1995	Hamelinck 2003	Dowaki 2004	**Ref.**
Type of gasifier																						
Fixed bed/Fluidized bed		Fixed	Fixed	Fixed	Fixed	Fixed	**Fixed**	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	**Fluidized**	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	**Fluidized**
Design		Updraft	Downdraft	Downdraft	Downdraft	Updraft	**-**	BCL	BCL	BCL	BCL	BCL	**BCL**	PFB	PFB	PFB	PFB	PFB	PFB	PFB	PFB	**PFB**
Direct/indirect heating	-	Indirect	Indirect	Indirect	-	-	**Indirect**	Indirect	Indirect	Indirect	Indirect	Indirect	**Indirect**	-	Direct	Direct	Direct	Direct	Direct	Direct	-	**Direct**
Air-blown/oxygen-blown	-	Air	Air	Air	Air	Air	**Air**	Air	Air	Air	Air	Air	**Air**	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	-	**Oxygen**
Pressurized/Atmospheric	-	A	A	A	A	A	**A**	A	A	A	A	A	**A**	P	P	P	P	P	P	P	P	**P**
Mass balance																						
Biomass	kg_{dry}	100.0	100.0	100.0	100.0	100.0	**100.0**	100.0	100.0	100.0	100.0	100.0	**100.0**	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	**100.0**
Syngas	Nm^3	243.1	-	-	240.0	-	**240.0**	-	69.8	-	88.4	80.0	**79.4**	121.0	117.8	120.8	132.3	176.2	144.1	114.8	-	**132.4**
Net electricity generation	MWh	-					**-**	0.0	0.0		0.0		**0.0**		0.0	0.0	200.9	710.0				**0.0**
Methanol	kg	-					**-**	43.2	48.8		42.3		**44.8**		48.1	49.7	37.4	27.2				**49.7**
Operating conditions																						
Temperature	°C	-	900	900		-	**900**	-	1000	900	863	863	**906.5**	-	820	820	982	920	982	-	750	**879**
Pressure	bar	-	-	-		-		-	1.8	-	1.2	1.01	**1.3**	-	1.7	33.7	34.5	25	34.5	25	7	**23.1**
Equivalence ratio (E/R)	%	0.304	0.261	0.261	-	-	**0.300**	-	-	-	0.289	0.289	**0.300**	0.301	0.201	0.169	0.200	0.254	0.200	0.164	0.576	**0.258**
Steam-to-biomass ratio (S/B)	% $wt._{dry\ basis}$	-	-	-	-	-	**-**	-	0.517	-	0.019	0.019	**0.185**	0.000	0.067	0.067	0.300	0.801	0.300	0.369	-	**0.272**
Performance																						
CGE	%	53%-65%	-	-	65.2%	-	**60.0%**	-	57%-72%	-	62.3%	78.6%	**67.5%**	51-67%	62%-82%	62%-82%	51-73%	43-70%	80.0%	55.7%	72%	
MCE	%	-	-	-	-	-	**-**	49.7%	56.2%	-	48.7%	-	**51.5%**	-	55.4%	57.2%	43.0%	31.3%	-	-	-	**56.3%**

Characteristics of syngas	Unit													43.2	48.8	42.3	48.1	49.7	50.8	47.15		
LHV	MJ/Nm^3	4.0-5.8	-	-	4.4-5.7	6.2	**5.2**		14.6-18.0	-	12.7-17.7	17.7	**15.6**	7.6-9.9	9.5-11.5	9.3-11.4	6.7-10.0	3.9-7.5	10.0	8.7	8.4	**8.5**
N_2 content	% mol.	46.6%	-	-	-	49.0%	**47.8%**		0.0%	0.0%	0.0%	0.0%	**0.0%**	1.0%	1.7%	1.7%	0.0%	0.0%	0.0%	0.6%	6.3%	**1.4%**
Composition (dry, after treatment)																						
N_2	% mol.	46.6%	47.8%	47.8%	47.8%	49.0%	**47.6%**		0.0%	0.0%	0.0%	0.0%	**0.0%**	1.0%	1.7%	1.7%	0.0%	0.0%	0.0%	0.6%	6.3%	**1.4%**
H_2	% mol.	18.6%	11.8%	16.5%	17.0%	11.0%	**14.9%**		22.7%	21.4%	20.8%	20.8%	**21.1%**	32.4%	30.5%	23.7%	30.5%	46.2%	30.5%	26.0%	32.7%	**31.3%**
CO	% mol.	21.6%	21.4%	13.6%	20.3%	30.0%	**21.3%**		46.1%	43.5%	46.3%	46.3%	**44.9%**	30.2%	28.3%	20.9%	22.0%	22.1%	22.0%	18.7%	37.9%	**25.1%**
CO_2	% mol.	11.6%	12.6%	18.5%	12.6%	7.0%	**12.4%**		14.4%	13.6%	11.1%	11.1%	**12.4%**	30.6%	28.3%	34.9%	35.0%	30.8%	35.0%	40.6%	23.0%	**32.1%**
CH_4	% mol.	1.6%	5.6%	2.9%	2.3%	3.0%	**3.1%**		16.9%	16.0%	15.7%	15.7%	**15.9%**	2.9%	11.2%	18.8%	12.0%	1.0%	12.0%	12.3%	0.1%	**8.7%**
C_nH_m	% mol.	-	0.8%	0.7%	-	-	**0.8%**		-	5.5%	6.0%	6.0%	**5.8%**	2.9%	-	-	0.5%	-	0.4%	1.8%	-	**1.4%**
Total	% mol.	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**		100.0%	100.0%	100.0%	100.0%	**100.0%**	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Composition (wet, after treatment)																						
N_2	% wt.	53.8%	52.7%	52.7%	54.4%	54.8%	**53.4%**		0.0%	0.0%	0.0%	0.0%	**0.0%**	1.2%	2.1%	2.0%	0.0%	0.0%	0.0%	0.6%	7.9%	**1.7%**
H_2O	% wt.	10.9%	10.4%	10.4%	10.7%	10.6%	**10.5%**		12.2%	11.6%	11.7%	11.7%	**11.5%**	11.2%	11.7%	11.0%	11.3%	13.0%	11.3%	10.4%	11.8%	**11.3%**
H_2	% wt.	1.1%	0.7%	0.9%	1.0%	0.6%	**0.9%**		1.8%	1.6%	1.6%	1.6%	**1.6%**	2.3%	2.3%	1.7%	2.2%	3.9%	2.2%	1.7%	2.5%	**2.3%**
CO	% wt.	18.1%	17.0%	10.8%	16.6%	23.9%	**17.1%**		50.6%	45.7%	48.9%	48.9%	**47.4%**	30.5%	30.0%	20.6%	22.5%	25.9%	22.5%	17.7%	39.8%	**25.7%**
CO_2	% wt.	15.3%	15.7%	23.0%	16.2%	8.8%	**15.7%**		24.8%	22.4%	18.4%	18.4%	**20.5%**	48.5%	47.1%	54.2%	56.3%	56.6%	56.3%	60.2%	38.0%	**51.7%**
CH_4	% wt.	0.8%	2.5%	1.3%	1.1%	1.4%	**1.4%**		10.6%	9.6%	9.5%	9.5%	**9.6%**	1.7%	6.8%	10.6%	7.0%	0.6%	7.0%	6.6%	0.1%	**5.1%**
C_nH_m	% wt.	-	1.0%	0.9%	-	-	**1.0%**		-	9.1%	9.9%	9.9%	**9.5%**	4.6%	-	-	0.7%	-	0.7%	2.7%	-	**2.2%**
Total	% wt.	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**		100.0%	100.0%	100.0%	100.0%	**100.0%**	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Ultimate analysis (dry, after treatment)																						
C	% wt.	12.5%	14.3%	12.6%	12.4%	13.7%	**13.5%**		36.4%	40.3%	41.2%	41.2%	**40.8%**	31.3%	30.8%	31.6%	30.8%	27.0%	30.8%	31.2%	27.5%	**30.8%**
H	% wt.	2.5%	2.6%	2.6%	2.5%	2.1%	**2.6%**		5.8%	6.9%	7.0%	7.0%	**7.0%**	4.8%	5.3%	5.5%	5.4%	5.5%	5.4%	5.1%	3.8%	**5.2%**
O	% wt.	31.2%	30.3%	32.1%	30.8%	29.4%	**30.6%**		57.8%	52.7%	51.7%	51.7%	**52.2%**	62.7%	61.8%	60.9%	63.8%	67.5%	63.8%	63.1%	60.9%	**62.3%**
N	% wt.	53.8%	52.7%	52.7%	54.4%	54.8%	**53.4%**		0.0%	0.0%	0.0%	0.0%	**0.0%**	1.2%	2.1%	2.0%	0.0%	0.0%	0.0%	0.6%	7.9%	**1.7%**
Total	% wt.	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**		100.0%	100.0%	100.0%	100.0%	**100.0%**	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Molar mass	g/mol	24.8	26.4	26.4	25.3	25.9	**25.8**		22.4	23.6	23.4	23.4	**23.2**	24.6	23.3	25.2	24.3	20.8	24.3	26.6	23.2	**24.0**
Density	kg/Nm^3	1.150	1.150	1.150	1.150	1.150	**1.150**		1.150	1.150	1.150	1.150	**1.150**	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	**1.150**

Tab. 18.9 Summary of the performance of wood gasification to syngas and methanol synthesis (atmospheric fluidized bed gasifiers).

Operating conditions / Performance	Unit	Mehlin 2003	Reichenbach 2001						Hamelinck 2003	Williams 1995	Lv 2004	Wu 2001		Li 2004								Ref.
Type of gasifier																						
Fixed bed/Fluidized bed		Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	Fluidized	**Fluidized**
Design		-	BFB	BFB	BFB	BFB	BFB	BFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	CFB	**CFB**
Direct/indirect heating	-	-	Indirect	Indirect	Indirect	Direct	Direct	Direct	Direct	Direct	Indirect	-	-	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	Indirect	**Indirect**
Air-blown/oxygen-blown	-	-	Air	Air	Air	Air	Air	Air	Air	Air	Air	-	-	Air	Air	Air	Air	Air	Air	Air	Air	**Air**
Pressurized/Atmospheric	-	-	A	A	A	A	A	A	A	A	A	-	-	A	A	A	A	A	A	A	A	**A**
Mass balance																						
Biomass	kg_{dry}	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	**100.0**
Syngas	Nm^3	-	180.6	215.5	269.2	242.8	308.7	366.7	193.6	200.5	-	-	-	259.0	275.0	251.0	213.0	172.0	206.0	235.0	324.0	**244.5**
Net electricity generation	MWh	-																				
Methanol	kg	50.8																				**50.8**
Operating conditions																						
Temperature	°C	-	708	800	900	708	800	900	-	697	800	775	800	-	-	-	-	-	-	-	-	
Pressure	bar	-	-	-	-	-	-	-	1.3	1.01	-	-	-	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	
Equivalence ratio (E/R)	%	-	0.176	0.241	0.340	0.229	0.329	0.417	0.198	0.353	0.189	-	-	0.307	0.335	0.303	0.248	0.172	0.217	0.246	0.394	**0.276**
Steam-to-biomass ratio (S/B)	% $wt._{dry\ basis}$	-	-	-	-	0.426	0.587	0.729	-	1.371	1.798	-	-	-	0.257	-	-	-	-	-	-	**0.861**
Performance																						
CGE	%	-	46%	52%	51%	46%	52%	50%	-	90.0%	-	71%	71%	60%-64%	57%-60%	50%-54%	49%-59%	59%-63%	65%	61%	45%	**58.0%**
MCE	%	58.5%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**58.5%**

Characteristics	Unit																					
LHV	MJ/Nm^3		4.6-8.8	4.4-8.8	3.5-7.0	-	-	-	6.1	7.5	8.7	6.4	5.3-6.0	3.1-4.1	2.8-3.7	2.7-3.6	3.2-4.2	4.7-6.1	4.4-5.6	4.1-4.6	2.2-2.5	**5.4**
N_2 content	% mol.		48.0%	50.3%	56.3%	-	-	-	45.0%	-	-	48.0%	51.8%	51.8%	45.2%	54.6%	52.6%	53.9%	46.3%	45.4%	54.6%	**50.7%**
Composition (dry, after treatment)																						
N_2	% mol.		48.0%	50.3%	56.3%	50.7%	50.7%	50.7%	45.0%	50.7%	50.7%	48.0%	51.8%	51.8%	45.2%	54.6%	52.6%	53.9%	46.3%	45.4%	54.6%	**50.3%**
H_2	% mol.		10.0%	9.4%	8.7%	11.0%	11.1%	12.8%	16.5%	24.7%	15.7%	7.6%	7.2%	5.1%	6.0%	5.3%	5.3%	5.4%	6.3%	8.9%	7.6%	**7.7%**
CO	% mol.		20.7%	20.4%	15.7%	15.8%	14.4%	11.2%	19.0%	10.9%	19.9%	24.9%	21.2%	18.6%	19.8%	15.8%	18.5%	21.4%	24.5%	21.9%	12.8%	**19.4%**
CO_2	% mol.		14.8%	14.3%	15.4%	17.5%	19.5%	21.7%	15.1%	9.7%	8.5%	13.0%	13.1%	20.9%	24.7%	21.2%	19.8%	14.7%	17.9%	19.9%	23.5%	**17.4%**
CH_4	% mol.		6.5%	5.5%	3.9%	5.1%	4.3%	3.6%	3.1%	3.9%	3.7%	5.9%	6.3%	3.7%	4.3%	3.2%	3.8%	4.6%	5.0%	3.9%	1.5%	**4.3%**
C_nH_m	% mol.		-	-	-	-	-	-	1.2%	0.2%	1.5%	0.6%	0.4%	-	-	-	-	-	-	-	-	**0.8%**
Total	% mol.		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Composition (wet, after treatment)																						
N_2	% wt.		51.9%	54.2%	59.7%	54.2%	53.7%	53.7%	50.3%	62.2%	57.9%	51.2%	55.2%	52.3%	45.1%	55.1%	53.4%	56.1%	47.9%	47.2%	55.1%	**52.5%**
H_2O	% wt.		9.6%	9.6%	9.4%	9.5%	9.4%	9.4%	9.9%	10.9%	10.1%	9.5%	9.5%	9.0%	8.9%	9.0%	9.0%	9.2%	9.2%	9.2%	9.0%	**9.2%**
H_2	% wt.		0.6%	0.5%	0.4%	0.6%	0.6%	0.7%	1.0%	1.6%	0.9%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.5%	0.4%	**0.4%**
CO	% wt.		16.4%	15.8%	11.3%	12.2%	11.0%	8.6%	15.9%	9.7%	16.4%	19.5%	16.1%	13.4%	14.8%	11.1%	13.3%	15.6%	18.8%	17.0%	9.0%	**14.6%**
CO_2	% wt.		18.5%	17.5%	17.5%	21.3%	23.4%	26.1%	19.8%	13.4%	11.0%	16.0%	15.7%	23.6%	29.0%	23.3%	22.4%	16.8%	21.6%	24.3%	25.9%	**20.4%**
CH_4	% wt.		3.0%	2.5%	1.6%	2.2%	1.9%	1.6%	1.5%	2.0%	1.8%	2.7%	2.7%	1.5%	1.8%	1.3%	1.6%	1.9%	2.2%	1.7%	0.6%	**1.8%**
C_nH_m	% wt.		-	-	-	-	-	-	1.6%	0.3%	1.9%	0.7%	0.5%	-	-	-	-	-	-	-	-	**1.0%**
Total	% wt.		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Ultimate analysis (wet, after treatment)																						
C	% wt.		14.3%	13.4%	10.9%	12.7%	12.5%	11.9%	14.7%	9.5%	12.9%	15.3%	13.6%	13.3%	15.6%	12.1%	13.0%	12.7%	15.6%	15.2%	11.4%	**14.0%**
H	% wt.		2.4%	2.2%	1.9%	2.2%	2.1%	2.1%	2.8%	3.3%	2.8%	2.3%	2.2%	1.6%	1.8%	1.6%	1.7%	1.8%	1.9%	2.0%	1.5%	**2.1%**
O	% wt.		31.4%	30.3%	27.6%	30.9%	31.7%	32.2%	32.3%	25.0%	26.4%	31.2%	29.0%	32.8%	37.5%	31.3%	31.9%	29.4%	34.6%	35.6%	32.0%	**31.4%**
N	% wt.		51.9%	54.2%	59.7%	54.2%	53.7%	53.7%	50.3%	62.2%	57.9%	51.2%	55.2%	52.3%	45.1%	55.1%	53.4%	56.1%	47.9%	47.2%	55.1%	**52.5%**
Total	% wt.		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	**100.0%**
Molar mass	g/mol		27.0	27.2	27.8	27.4	27.7	27.7	25.9	22.7	25.1	27.5	27.5	29.6	29.9	29.6	29.3	28.4	28.6	28.4	29.6	**28.0**
Density	kg/Nm^3		1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	**1.150**

18.4.5 LCI of ‘Synthetic gas plant’

The process ‘Synthetic gas plant’ includes the requirements for materials for the infrastructure, estimates on energy use for construction (diesel in building machine and on-site electricity consumption), supply of materials to construction site, dismantling of plant and recycling/disposal, and finally land use and occupation of the plant. The lifetime of the plant is taken as 50 years.

Due to a lack of data (hardly any commercial experience, demonstration stage, no specific study on the construction of such plants, even demonstration plants). The synthetic gas plant is modelled on the basis of the process ‘industrial furnace, coal, 1-10 MW’, the technology of which is supposed to be relatively similar, as far as the reactor is concerned at least. In order to take into account the drying and size reduction stages as well as the post-gasification gas treatment and conditioning, a factor 2 is applied to each raw unit data. Standard distances (ecoinvent Centre 2004) are used for the supply of all primary materials[46]. Land transformation and occupation are adapted.

The thermal output (syngas production) capacity of the plant is considered to be 5 MW_{th}, which corresponds to an input (feed) capacity of 7.2-7.6 MW_{th} of wood, depending on the technology (fixed bed or fluidized bed). The plant processes some 32-35 t/day of fresh wood chips to 80’000-83’000 Nm^3/day of syngas (330 days/yr). The infrastructure is not specific to the technology. The unit process raw data of 'synthetic gas plant’ is indicated in Tab. 18.10.

Tab. 18.10 Unit process raw data of the datasets ‘synthetic gas plant’.

	Name	Location	InfrastructureProcess	Unit	synthetic gas plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	synthetic gas plant	CH	1	unit	1.00E+0			
resource, land	Occupation, industrial area, built up	-	-	m2a	1.20E+5	1	1.89	(3,5,4,2,4,na); Adapted from 'Industrial furnace, coal, 1-10 MW', factor 2, 50 yrs lifetime
	Occupation, industrial area, vegetation	-	-	m2a	1.20E+5	1	1.89	
	Occupation, construction site	-	-	m2a	9.60E+3	1	1.89	
	Transformation, from unknown	-	-	m2	4.80E+3	1	2.34	
	Transformation, to industrial area, built up	-	-	m2	2.40E+3	1	2.34	
	Transformation, to industrial area, vegetation	-	-	m2	2.40E+3	1	2.34	
technosphere	concrete, normal, at plant	CH	0	m3	3.60E+2	1	1.64	
	diesel, burned in building machine	GLO	0	MJ	1.08E+6	1	1.64	
	electricity, medium voltage, at grid	CH	0	kWh	6.00E+4	1	1.64	
	aluminium, production mix, at plant	RER	0	kg	7.20E+2	1	1.64	
	copper, at regional storage	RER	0	kg	1.80E+3	1	1.64	
	reinforcing steel, at plant	RER	0	kg	5.40E+4	1	1.64	
	steel, low-alloyed, at plant	RER	0	kg	1.80E+4	1	1.64	
	heat, light fuel oil, at industrial furnace 1MW	CH	0	MJ	1.08E+6	1	1.64	
	disposal, aluminium, 0% water, to sanitary landfill	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Implemented according to consumption of aluminium, 40%
	disposal, aluminium, 0% water, to municipal incineration	CH	0	kg	0	1	1.64	
	disposal, copper, 0% water, to municipal incineration	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Implemented according to consumption of copper
	disposal, steel, 0% water, to inert material landfill	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Implemented according to consumption of steel, 40%
	disposal, steel, 0% water, to municipal incineration	CH	0	kg	0	1	1.64	
	disposal, building, reinforcement steel, to final disposal	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Implemented according to consumption of reinforcement
	disposal, building, reinforcement steel, to recycling	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Adapted from 'Industrial furnace, coal, 1-10 MW'
	disposal, building, reinforcement steel, to sorting plant	CH	0	kg	5.40E+4	1	1.64	
	disposal, concrete, 5% water, to inert material landfill	CH	0	kg	0	1	1.64	(3,5,4,2,4,na); Calculation according to consumption and density of steel
	disposal, building, concrete, not reinforced, to sorting plant	CH	0	kg	8.57E+5	1	1.64	
	transport, freight, rail	CH	0	tkm	4.44E+4	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	2.09E+4	1	2.09	
emission air, high population density	Heat, waste	-	-	MJ	2.16E+5	1	1.05	(1,1,1,1,1,na); Calculation

18.4.6 LCI of ‘Synthetic gas, from wood, at fixed bed gasifier’

The inventory of ‘synthetic gas, from wood, at fixed bed gasifier’ is compiled by cross-checking of various references from the literature, indicated along the chapter. Most of the references are reported in Tab. 18.8 and Tab. 18.9, together with their most relevant results.

The process ‘synthetic gas, from wood, at fixed bed gasifier’ considers the production of syngas by gasification of mixed wood chips, including drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), fixed bed gasification of the wood chips and treatment of the resulting syngas to remove impurities and contaminants. Composition (% mol.) of the resulting syngas is 28.4% H_2, 40.6% CO, 23.6% CO_2, 5.9% CH_4 and 1.5% C_nH_m on a nitrogen and water free basis. Nitrogen (from air input) content is 47.6% (mol.). Energy content of the gas is 5.2

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[46] Transport distances are 20 km by road (28t) for concrete (2'380 kg/m^3), 200 km by rail and 50 km by road (28t) for aluminium, and 600 km by rail and 50 km by road (28t) for copper and steel.

MJ/Nm^3. The inventory refers to the production of 1 Nm^3 of syngas by atmospheric indirectly heated fixed bed gasification.

As indicated before, wood chips supplied to the gasification plant consist of 64% 'wood chips, mixed, u=120%, at forest', 22% 'wood chips, mixed, from industry, u=40%, at plant' and 14% 'waste wood chips, mixed, u=40%, at plant'. Given the respective proportions, 'u' ratios and bulk densities of each quality of wood chips and given the yield (2.4 Nm^3 of syngas per kg of dry wood chips) and density (1.15 kg/Nm^3) of syngas, the volumes of wood chips (see Fig. 18.9) are given as follows:

- 'wood chips, mixed, u=120%, at forest': 1.414 x 10^{-3} m^3
- 'wood chips, mixed, from industry, u=40%, at plant': 4.860 x 10^{-4} m^3
- 'waste wood chips, mixed, from industry, u=40%, at plant': 3.093 x 10^{-4} m^3

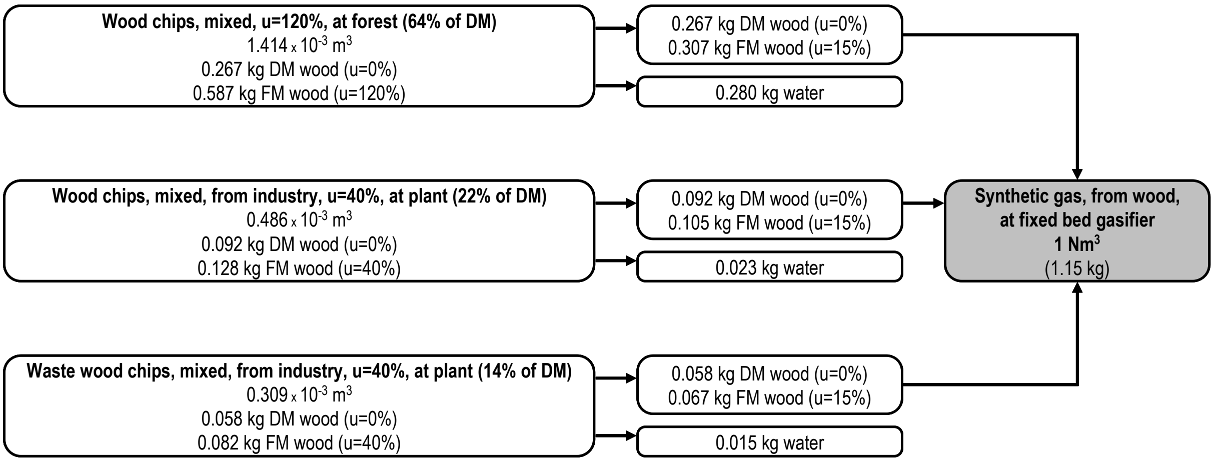


Fig. 18.9 Yield of synthetic gas in fixed bed gasification of wood chips.

According to ecoinvent standards for the supply of wood, the transport distance from either the forest or the chopping facility to the gasification plant is taken as 50 km. The transport is performed by 28t truck. Given the respective apparent densities of the different qualities of chips (see Tab. 18.4), the effective weight of wood transported to the gasification plant (prior to drying) is equal to:

$$1.414 \cdot 10^{-3} \times 414.9 + 4.860 \cdot 10^{-4} \times 264.0 + 3.093 \cdot 10^{-4} \times 264.0 = 0.657 \text{ kg/Nm}^3 \text{ of syngas}$$

In the first stage of the process, the chips need to be dried down to a moisture content of 10-15% (wt.) water, or u=15% (see Fig. 18.9). Steam drying is used. The amount of steam is calculated according to the amount of water to evaporate, and is given by: 2.8 MJ/kg water evaporated (Hamelinck 2001).

The amount of heat required for drying purposes is equal to:

$$2.8 \times (0.280 + 0.023 + 0.015) = 0.890 \text{ MJ/Nm}^3 \text{ of syngas}$$

In the present study, the heat for drying is considered to be supplied by waste heat from the gasification process. Therefore, the net heat consumption for drying is zero.

The drying process also consumes electricity at a rate of 0.025 kWh per kg of water evaporated (i.e. 7.938 x 10^{-3} kWh/Nm^3 of syngas). According to the feed size requirements of the gasifier (30x30x30 mm), further comminution by crushing must be performed. The corresponding electricity consumption is 7.2 kWh per ton of incoming wood (after drying, u=15%), i.e. 3.450 x 10^{-3} kWh/Nm^3 of syngas.

As far as the gasification process is concerned, a typical E/R ratio (see paragraph 18.4.4 and Tab. 18.8) of 0.3 is considered, resulting from an extensive literature survey. Also, the steam:biomass (S/B) ratio is taken as 0.861, like in the case of the fluidised bed gasifier (supposition due to the lack of data concerning fixed bed gasifiers). Again, the supply of heat is ensured by the combustion of wood chips. With a value of 2.6 MJ/kg of steam (heat), the amount of heat for the gasification reaction is given by:

$$2.6 \times 0.861 / 2.4 = 0.933 \text{ MJ/Nm}^3 \text{ of syngas}$$

According to the literature survey and given the typical composition of wood (see Tab. 18.4), the amount of fly ash collected at the bottom of the cyclone is taken as 8.941 g/kg for softwood and 4.850 g/kg for hardwood. In accordance with hypotheses in other processes (e.g. wood, burned in furnace), it is considered that 60% of the fly ash is disposed of in municipal incineration and 40% is disposed of in sanitary landfill.

According to (Reichenbach de Sousa 2001), Argon (Ar) may be added to the gasifier as a stabilizing agent proportionally to the air injected to the gasifier (data from a laboratory scale gasification unit). The use of Ar, however, is likely to be limited to laboratory experiments (for easier measurements) and is not taken into account in the present inventory.

The gas treatment technology considered is low temperature wet gas cleaning. The syngas goes by a series of treatment stages as indicated in paragraph 18.4.3.

The amount of water contacted with the gas in the wet scrubber is taken as 0.284 kg/kg of dry wood chips (Giordano 1998), i.e. 0.118 kg/Nm^3 of syngas. The water, charged with impurities absorbed from the syngas is sent to a standard wastewater treatment plant, class 2. Due to a lack of data concerning wastewater, the standard wastewater “quality” is taken into account. Within the scrubbing process, soda (NaOH) is added to get rid of H_2S and HCl. Similarly, sulphuric acid is added to get rid of NH_3, CS_2 and HCN. The amounts of NaOH and H_2SO_4 are calculated from the typical raw syngas composition as indicated in Tab. 18.11. The consumptions of pure (100%) NaOH and H_2SO_4 are taken respectively as 1.2 times the amount of HCl and H_2S and 1.2 times the amounts of NH_3, COS and CS_2.

Tab. 18.11 Typical raw syngas impurities from the gasification of wood (Boerrigter 2002).

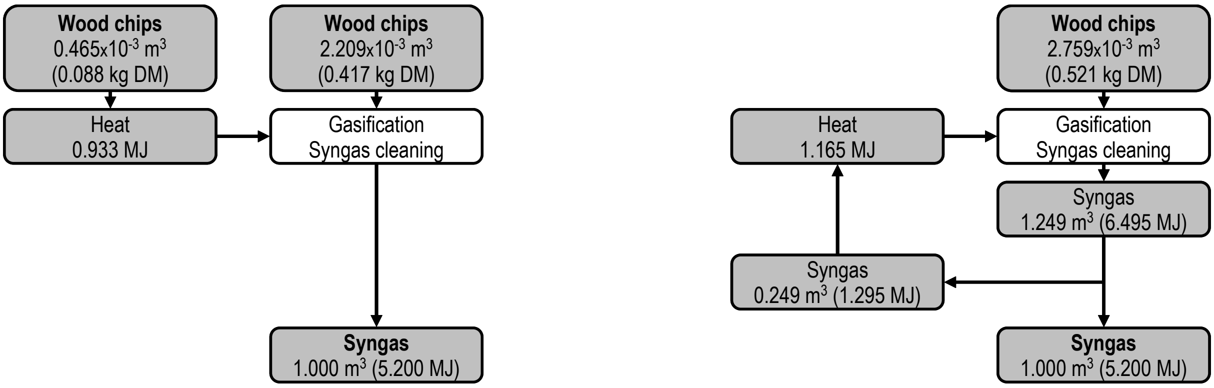
Impurities	Concentration [mg/Nm^3]
NH_3	2'200
HCl	130
H_2S	150
COS, CS_2, HCN, HBr	< 25
Dust, soot, ash	2'000
Tars	
Class 1	330
Class 2	350
Class 3	370
Class 4	5'300
Class 5	2'250

Electricity consumption within the gasification process itself is concerned with air compression (0.009 kWh/kg dry feed, i.e. 3.750×10^{-3} kWh/Nm^3 of syngas) and general pumping (0.0165 kWh/kg dry feed, i.e. 6.875×10^{-3} kWh/Nm^3 of syngas).

Tab. 18.12 Summary of heat and electricity use in the dataset 'synthetic gas, from wood, at fixed bed gasifier'.

Process stages	Heat consumption (MJ/Nm^3 syngas)	Electricity consumption (kWh/Nm^3 syngas)
Drying	-	7.938E-03
Comminution		3.450E-03
Air compression		3.750E-03
Pumping		6.875E-03
Gasification	9.328E-01	
Total (net)	9.328E-01	2.201E-02

It is considered here that the net heat required for the entire process (i.e. 0.933 MJ/Nm^3) is supplied by syngas combustion (after the cleaning process). From the point of view of furnace emissions, syngas offers a much cleaner combustion than wood chips, thereby reducing significantly dusts and particle emissions. As indicated in Fig. 18.10, the gross production of syngas is 1.249 Nm^3 of which 1 Nm^3 is the net production and 0.249 Nm^3 is used to provide the required heat for gasification. As a result, compared to what is described above, all the inputs to the process (and the outputs such as wood ash) are multiplied by a factor of 1.249, including heat, wood chips for syngas production, electricity, water, chemicals, etc. The resulting inputs to the process are given in Fig. 18.10.



Heat supply through wood combustion

Heat supply through syngas combustion

Fig. 18.10 Heat-from-wood vs. heat-from-syngas in fixed bed gasification.

The process 'industrial furnace, natural gas' is used to describe the boiler. The efficiency of syngas combution is taken as 90%.

Emissions relating to syngas combustion are considered according to the composition of syngas, as indicated in Tab. 18.6:

- CO (17.1% wt. or 0.197 kg/Nm^3) is considered to be converted completely to CO_2;
- CO_2 (15.7% wt. or 0.181 kg/Nm^3) does not react in the combustion process and is therefore emitted as such;
- CH_4 and C_nH_m altogether (2.4% wt. or 0.028 kg/Nm^3, or yet 1.416 MJ/Nm^3) are considered as 'natural gas' and described according to the emissions of the process 'natural gas, burned in industrial furnace >100kW' (emissions only);
- H_2 is converted to water; however, according to the hypotheses in the methanol from natural gas process, additional NO_x emissions relating to the combustion of H_2 are considered, of 0.213 mg NO_x per kg H_2.

Global CO_2 emissions are corrected such that the overall carbon balance of the process is closed. Some carbon indeed ends up in the waste streams and effluents. This carbon is considered to be burned in one way or another, downstream of the gasification process (at the wastewater treatment or incineration plant, for example), and therefore ends up as CO_2. Total CO_2 emissions amount to 0.374 kg CO_2 per net Nm^3 of syngas. They are considered to be emitted to air, high population density, just like the other emissions from the combustion process.

The overall amount of waste heat (emitted to air, high population density) is determined according to the energy balance based on the higher heating value of inputs and outputs. Waste heat of the gasification process is 3.406 MJ per net Nm^3 of syngas, while the heat of syngas combustion is 1.295 MJ per net Nm^3 of syngas. Finally, it is considered that all electricity consumption is generating waste heat (to air, high population density) of the same amount of energy, according to the ecoinvent guidelines.

It is worth noting that the possible contamination of waste wood (compared to forest or residual wood) has little effect on the performance of the gasification process (Reichenbach de Sousa 2001; De Sousa 2002). Considering that waste wood represents only 14% of the feed to the gasifier, the effect of possible wood contamination is not taken into account.

According to the configuration described above, the gasification of 1 kg mixed wood chips (dry matter) in a fixed bed gasifier, as described in the present dataset, generates 1.922 net Nm^3 of syngas, with the composition indicated in Tab. 18.6. The lower heating value of the gas is 5.2 MJ/Nm^3. The gas is at atmospheric pressure.

The overall energy efficiency of the process is 49.5%.

The unit process raw data of 'synthetic gas, from wood, at fixed bed gasifier' is indicated in Tab. 18.13.

Tab. 18.13 Unit process data of the dataset 'synthetic gas, from wood, at fixed bed gasifier'.

	Name	Location	InfrastructureProcess	Unit	synthetic gas, from wood, at fixed bed gasifier	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	synthetic gas, from wood, at fixed bed gasifier	CH	0	Nm3	1.00E+0			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	2.75E-2	1	1.33	(3,3,1,2,3,5); Several literature sources
	synthetic gas plant	CH	1	unit	9.12E-10	1	3.18	(4,5,1,2,3,5); Calculated from the production and input capacity of the reference plant
	wood chips, mixed, u=120%, at forest	RER	0	m3	1.77E-3	1	1.31	(2,3,1,2,3,5); Yield from literature survey, distribution from IEA Task 33 CH report
	wood chips, mixed, from industry, u=40%, at plant	RER	0	m3	6.07E-4	1	1.31	
	waste wood chips, mixed, from industry, u=40%, at plant	CH	0	m3	3.86E-4	1	1.31	
	industrial furnace, natural gas	RER	1	unit	1.89E-9	1	3.15	(3,5,1,2,3,5); Calculation based on energy demand of the process
	tap water, at user	CH	0	kg	1.48E-1	1	1.40	(3,5,1,2,3,5); Weak data, one literature reference only (pilot plant)
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	8.39E-4	1	1.33	(3,3,1,2,3,5); Calculated from a typical quality of untreated syngas from wood
	sulphuric acid, liquid, at plant	RER	0	kg	3.33E-3	1	1.33	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.31E-3	1	1.31	(2,3,1,2,3,5); Average of several literature sources
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	1.75E-3	1	1.31	
	transport, freight, rail	CH	0	tkm	3.69E-3	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	4.18E-2	1	2.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.01E-4	1	1.44	(4,5,1,2,3,5); Weak data, specific quality of waste water was not considered
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.74E-1	1	1.30	(1,1,1,2,3,5); Calculation, to close carbon balance
	Acetaldehyde	-	-	kg	3.55E-10	1	2.42	(4,5,4,3,5,5); Calculation, from syngas composition and natural gas combustion
	Acetic acid	-	-	kg	5.33E-8	1	2.42	
	Benzene	-	-	kg	1.42E-7	1	2.42	
	Benzo(a)pyrene	-	-	kg	3.55E-12	1	3.85	
	Butane	-	-	kg	2.49E-7	1	2.42	
	Carbon monoxide, biogenic	-	-	kg	7.46E-7	1	5.99	
	Dinitrogen monoxide	-	-	kg	3.55E-8	1	2.42	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	1.07E-17	1	3.85	
	Formaldehyde	-	-	kg	3.55E-8	1	2.42	
	Mercury	-	-	kg	1.07E-11	1	5.99	
	Methane, biogenic	-	-	kg	7.11E-7	1	2.42	
	Nitrogen oxides	-	-	kg	6.36E-6	1	2.42	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	3.55E-9	1	3.85	
	Particulates, < 2.5 um	-	-	kg	7.11E-8	1	3.85	
	Pentane	-	-	kg	4.26E-7	1	2.42	
	Propane	-	-	kg	7.11E-8	1	2.42	
	Propionic acid	-	-	kg	7.11E-9	1	2.42	
	Sulfur dioxide	-	-	kg	1.95E-7	1	2.19	
	Toluene	-	-	kg	7.11E-8	1	2.42	
	Heat, waste	-	-	MJ	4.80E+0	1	1.30	(1,1,1,2,3,5); Based on ecoinvent Guidelines and energy balance closure

18.4.7 LCI of 'Synthetic gas, from wood, at fluidized bed gasifier'

The inventory of 'synthetic gas, from wood, at fluidized bed gasifier' is compiled by cross-checking of various references from the literature, indicated along the chapter. Most of the references are reported in Tab. 18.8 and Tab. 18.9, together with their most relevant results.

Just like ‘synthetic gas, from wood, at fixed bed gasifier’, the process ‘synthetic gas, from wood, at fluidized bed gasifier’ considers the production of 1 Nm^3 of syngas by gasification of mixed wood chips, including drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), fluidized bed gasification of the chips and treatment of the resulting syngas to remove impurities and contaminants. Composition (% mol.) of the syngas is 15.5% H_2, 39.2% CO, 34.9% CO_2, 8.7% CH_4 and 1.7% C_nH_m on a nitrogen and water free basis. Nitrogen content is 50.4%. Energy content of the gas is 5.4 MJ/Nm^3. The inventory refers to the production of 1 Nm^3 of syngas by atmospheric indirectly heated fluidized bed gasification.

Given the respective proportions, ‘u’ ratios and bulk densities of each quality of wood chips and given the yield (2.445 kg of syngas per kg of dry wood chips) and density (1.15 kg/Nm^3) of syngas (see Fig. 18.11), the volumes of wood chips are given as follows:

- ‘wood chips, mixed, u=120%, at forest’: 1.388×10^{-3} m^3
- ‘wood chips, mixed, from industry, u=40%, at plant’: 4.771×10^{-4} m^3
- ‘waste wood chips, mixed, from industry, u=40%, at plant’: 3.036×10^{-4} m^3

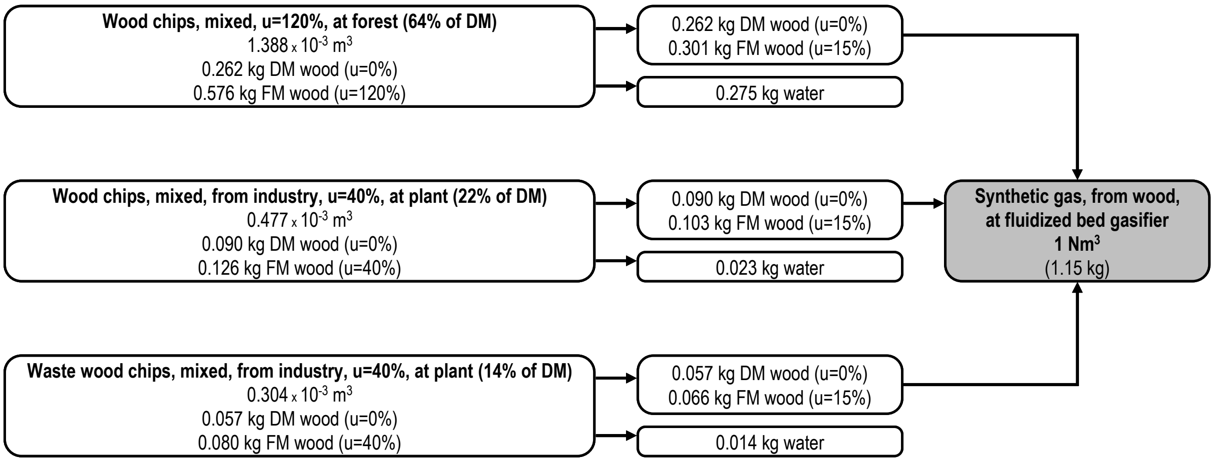


Fig. 18.11 Yield of synthetic gas in fluidized bed gasification of wood chips.

According to ecoinvent standards for the supply of wood, the transport distance from either the forest or the chopping facility to the gasification plant is taken as 50 km. The transport is performed by 28t truck. Given the respective apparent densities of the different qualities of chips (see Tab. 18.4), the effective weight of wood transported to the gasification plant (prior to drying) is equal to:

$$1.388 \cdot 10^{-3} \times 414.9 + 4.771 \cdot 10^{-4} \times 264.0 + 3.036 \cdot 10^{-4} \times 264.0 = 0.645 \text{ kg/Nm}^3 \text{ of syngas}$$

Since the processes of wood drying, comminution and gas treatment are identical to the fixed bed technology, the reader is advised to refer to paragraph 18.4.6 for the various hypotheses concerning these specific stages. The equivalence ratio (E/R) is here equal to 0.276, while the steam-to-biomass ratio (S/B) is taken as 0.861 (see Tab. 18.9). The main difference between the fluidized bed gasifier and the fixed bed one is the presence of a circulating bed within the gasifier. The bed mainly consists of sand which carries the heat for the process in a circulating effect. As the sand is circulating within the reactor, it gets charged with impurities and needs to be regularly partially renewed. The amount of sand is taken as 25 g per kg of dry feed or 10.2 g/Nm^3 of syngas.

Tar cracking is considered as the first stage of the gas cleaning process. Tar cracking is performed in a reactor where the gas is contacted with a material bed consisting of 83% dolomite and 17% zeolite (acting as a catalyst for tar decomposition). The average amount of dolomite (according to the indicated renewal rate) is taken as 20.2 g/kg dry feed (average of three values from the literature: 9.5, 26.8 and 24.2 g/kg dry feed) or 8.2 g/Nm^3 of syngas.

Like in the case of fixed bed gasification, it is considered here that the heat required for drying ius supplied by waste heat from the gasification process, and therefore, the net heat consumption of that stage is zero. The consumptions of heat and electricity of the fluidized bed gasification of wood chips are summarised in Tab. 18.14 below.

Tab. 18.14 Summary of heat and electricity use in the dataset 'synthetic gas, from wood, at fluidized bed gasifier'.

Process stages	Heat consumption (MJ/Nm^3 syngas)	Electricity consumption (kWh/Nm^3 syngas)
Drying	-	7.791E-03
Comminution		3.387E-03
Air compression		3.681E-03
Pumping		6.748E-03
Gasification	9.156E-01	
Total (net)	9.156E-01	2.161E-02

The net heat required for the entire process (i.e. 0.916 MJ/Nm^3) is supplied by syngas combustion (after gas cleaning). As indicated in Fig. 18.12, the gross production of syngas is 1.582 Nm^3 of which 1 Nm^3 is the net production and 0.582 Nm^3 is used to provide the required heat for gasification. As a result, compared to what is described above, all the inputs to the process (and the outputs such as wood ash) are multiplied by a factor of 1.582, including heat, wood chips for syngas production, electricity, water, chemicals, etc. The resulting inputs to the process are given in Tab. 18.15.

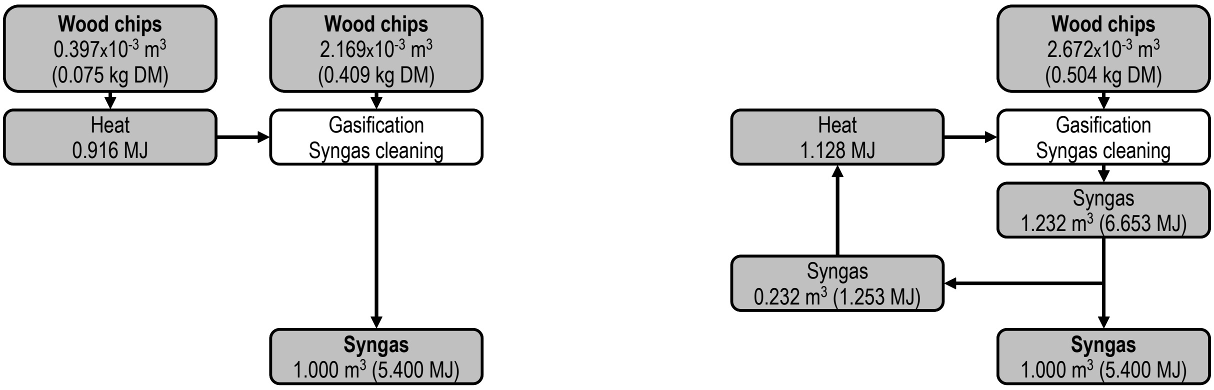


Fig. 18.12 Heat-from-wood vs. heat-from-syngas in fluidised bed gasification.

Again, the process 'industrial furnace, natural gas' is used to describe the boiler and the efficiency of syngas combution is taken as 90%.

Concerning missions relating to syngas combustion, the same approach as for fixed bed gasification is applied: CO is converted to CO_2, CO_2 does not react and is emitted as such, CH_4 and other hydrocarbons (C_nH_m) are considered as 'natural gas, burned in industrial furnace'.

Like in the case of fixed bed gasification, total CO_2 emissions are corrected such that the overall carbon balance of the process is closed. Direct CO_2 emissions amount to 0.322 kg CO_2 per net Nm^3 of syngas. They are considered to be emitted to air, low population density, just like the other emissions from the combustion process.

Similarly, waste heat of the gasification process amounts to 2.934 MJ per net Nm^3 of syngas, while the heat of syngas combustion is 1.253 MJ per net Nm^3 of syngas. Finally, all electricity consumption is generating waste heat (to air, high population density) of the same amount of energy.

The gasification of 1 kg mixed wood chips (dry matter) in a fluidized bed gasifier, as described in the present dataset, generates 1.545 net Nm^3 of syngas, with the composition indicated in Tab. 18.6. The lower heating value of the gas is 5.4 MJ/Nm^3. The gas is at atmospheric pressure.

The overall energy efficiency of the process is 53.1%.

The unit process raw data of 'synthetic gas, from wood, at fluidized bed gasifier' is indicated in Tab. 18.15.

Tab. 18.15 Unit process data of the dataset 'synthetic gas, from wood, at fluidized bed gasifier'.

	Name	Location	InfrastructureProcess	Unit	synthetic gas, from wood, at fluidized bed gasifier	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	synthetic gas, from wood, at fluidized bed gasifier	CH	0	Nm3	1.00E+0			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	2.66E-2	1	1.33	(3,3,1,2,3,5); Several literature sources
	synthetic gas plant	CH	1	unit	9.33E-10	1	3.18	(4,5,1,2,3,5); Calculated from the production and input capacity of the reference plant
	wood chips, mixed, u=120%, at forest	RER	0	m3	1.71E-3	1	1.31	(2,3,1,2,3,5); Yield from literature survey, distribution from IEA Task 33 CH report
	wood chips, mixed, from industry, u=40%, at plant	RER	0	m3	5.88E-4	1	1.31	
	waste wood chips, mixed, from industry, u=40%, at plant	CH	0	m3	3.74E-4	1	1.31	
	industrial furnace, natural gas	RER	1	unit	1.89E-9	1	3.15	(3,5,1,2,3,5); Calculation based on energy demand of the process
	tap water, at user	CH	0	kg	1.43E-1	1	1.40	(3,5,1,2,3,5); Weak data, one literature reference only (pilot plant)
	dolomite, at plant	RER	0	kg	1.02E-2	1	1.40	(4,4,1,2,3,5); Average of several literature sources
	zeolite, powder, at plant	RER	0	kg	2.08E-3	1	1.40	
	silica sand, at plant	DE	0	kg	1.26E-2	1	1.40	
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	8.28E-4	1	1.33	(3,3,1,2,3,5); Calculated from a typical quality of untreated syngas from wood
	sulphuric acid, liquid, at plant	RER	0	kg	3.29E-3	1	1.33	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.24E-3	1	1.31	(2,3,1,2,3,5); Average of several literature sources
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	1.69E-3	1	1.31	
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	2.28E-2	1	1.44	(4,5,1,2,3,5); Estimate for the disposal of gasifier bed material
	disposal, zeolite, 5% water, to inert material landfill	CH	0	kg	2.08E-3	1	1.44	
	transport, freight, rail	CH	0	tkm	3.52E-3	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	4.13E-2	1	2.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	6.09E-5	1	1.44	(4,5,1,2,3,5); Weak data, specific quality of waste water was not considered
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	3.22E-1	1	1.30	(1,1,1,2,3,5); Calculation, to close carbon balance
	Acetaldehyde	-	-	kg	3.89E-10	1	2.42	(4,5,4,3,5,5); Calculation, from syngas composition and natural gas combustion
	Acetic acid	-	-	kg	5.84E-8	1	2.42	
	Benzene	-	-	kg	1.56E-7	1	2.42	
	Benzo(a)pyrene	-	-	kg	3.89E-12	1	3.85	
	Butane	-	-	kg	2.73E-7	1	2.42	
	Carbon monoxide, biogenic	-	-	kg	8.18E-7	1	5.99	
	Dinitrogen monoxide	-	-	kg	3.89E-8	1	2.42	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	1.17E-17	1	3.85	
	Formaldehyde	-	-	kg	3.89E-8	1	2.42	
	Mercury	-	-	kg	1.17E-11	1	5.99	
	Methane, biogenic	-	-	kg	7.79E-7	1	2.42	
	Nitrogen oxides	-	-	kg	6.97E-6	1	2.42	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	3.89E-9	1	3.85	
	Particulates, < 2.5 um	-	-	kg	7.79E-8	1	3.85	
	Pentane	-	-	kg	4.67E-7	1	2.42	
	Propane	-	-	kg	7.79E-8	1	2.42	
	Propionic acid	-	-	kg	7.79E-9	1	2.42	
	Sulfur dioxide	-	-	kg	2.14E-7	1	2.19	
	Toluene	-	-	kg	7.79E-8	1	2.42	
	Heat, waste	-	-	MJ	4.28E+0	1	1.30	(1,1,1,2,3,5); Based on ecoinvent Guidelines and energy balance closure

18.4.8 LCI of 'Synthetic gas, production mix, at plant'

As indicated in paragraph 18.4.2, gasification experience in Switzerland, so far, has been limited to research and development and to two pilot-demonstration plants, the Pyroforce and the Xylowatt gasifier (Bühler 2004), both gasifiers being of the fixed bed type. There is therefore no actual production mix as such. As there is no reason to favour one technology, the hypothesis is made that, in the short-to-medium term (towards 2010), with the development of gasification, both the fluidized bed and the fixed bed technologies could have a similar role to play in terms of production volume. As discussed in paragraph 18.4.3, fixed bed gasification is more adapted to small scale decentralized applications, whereas fluidized bed gasification will suit more larger scale applications (e.g. production of synthesis fuels such as methanol, Fischer-Tropsch, DME, etc.). As a result, the production mix is considered to be divided in equal shares between syngas from fixed bed and syngas from fluidized bed. The unit process raw data of 'synthetic gas, production mix, at plant' is indicated in Tab. 18.16.

Tab. 18.16 Unit process data of the dataset 'synthetic gas, production mix, at plant'.

	Name	Location	InfrastructureProcess	Unit	synthetic gas, production mix, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	synthetic gas, production mix, at plant	CH	0	Nm3	1.00E+0			
technosphere	synthetic gas, from wood, at fluidized bed gasifier	CH	0	Nm3	5.00E-1	2	1.31	(4,5,na,na,na,na); Arbitrary hypothesis
	synthetic gas, from wood, at fixed bed gasifier	CH	0	Nm3	5.00E-1	3	1.31	

18.5 Biomethanol from syngas

18.5.1 Characterisation of biomethanol

The present section aims at characterising the most significant physical and chemical characteristics of methanol as a fuel for transportation, such as the density, energy content.

Methanol (CH_3OH, CAS-No. 67-56-1, synonyms: methyl alcohol, methyl hydroxide, monohydroxymethane) is a clear, colourless, volatile liquid with a faint alcohol-like odour. Methanol has long been produced commercially (world production is today over 47 billion l/yr) and is used in many industrial applications.

Methanol purity is generally understood as >99.9% (wt.), i.e. a water content less than 0.1% (wt.). The density of methanol is found vary between 0.792 (most frequent value) to 0.796 kg/l, while the lower heating value ranges between 19.8 and 20.1 MJ/kg, with 20.0 MJ/kg being the most cited value. The main characteristics of methanol are given in Tab. 18.17 below.

Tab. 18.17 Main characteristics of biomethanol.

basic unit in database		**Methanol** **kg**
Lower heating value (Hu)	MJ/kg	20.0
Upper heating value (Ho)	MJ/kg	22.7
Density 20°C	kg/l	0.792
Density 20°C	kg/m^3	792
Oxygen	kg/kg	0.500
Carbon, fossil	kg/kg	0.000
Carbon, biogen	kg/kg	0.375
Hydrogen	kg/kg	0.125
Sulphur	ppm	<.5
CO_2 Factor	kg/MJ (Hu)	0.0688
CO_2 Factor	kg/kg	1.38
Formula		CH_3OH
CAS		67-56-1
Source		*Malcom Pirnie Inc. 1999*

Methanol is generally made from natural gas. Methanol production from biomass (i.e. cellulosic material, mostly wood) is technically but not yet commercially feasible. Biomass gasification technology, indeed, is at the demonstration to early commercial stage, but the integration of biomass gasification with methanol production is only at the stage of research and development.

Independently from the nature of the feedstock, the current and future expected major uses and applications of syngas are discussed in paragraphs 18.4.2. Applications and use of biomethanol are treated in the next paragraph.

18.5.2 Applications and use of biomethanol

Currently, the majority of methanol is synthesized from syngas that is produced via steam reforming of natural gas (Althaus 2004). Methanol is a commodity chemical, one of the top ten chemicals produced globally. Methanol is an important chemical intermediate used to produce a number of chemicals, including formaldehyde, dimethyl ether, MTBE, ammonia, acetic acid, and olefins, etc. Formaldehyde production is the largest consumer of methanol (35% of worldwide methanol), followed by MTBE (25%) and acetic acid (9%). Methanol can also be used directly or blended with other petroleum products as a transportation fuel. The use of methanol as a fuel is not new, as it has been used for many years blended in various proportions to gasoline. Its main asset is as a potential clean burning fuel, suitable for gas turbines, internal combustion engines, and more specifically, for fuel cell applications for which it is a prime candidate.

Although in some countries, methanol fuel could be used in large-scale, current economics favour natural gas, which is still considered abundant and has greater advantages over methanol. Thus, on a worldwide basis, it is uncertain whether the methanol fuel market will expand significantly or remain relatively small and confined to specialised markets such as chemicals and fuel cells.

18.5.3 System definition

The system described in this paragraph is presented schematically in Fig. 18.13.

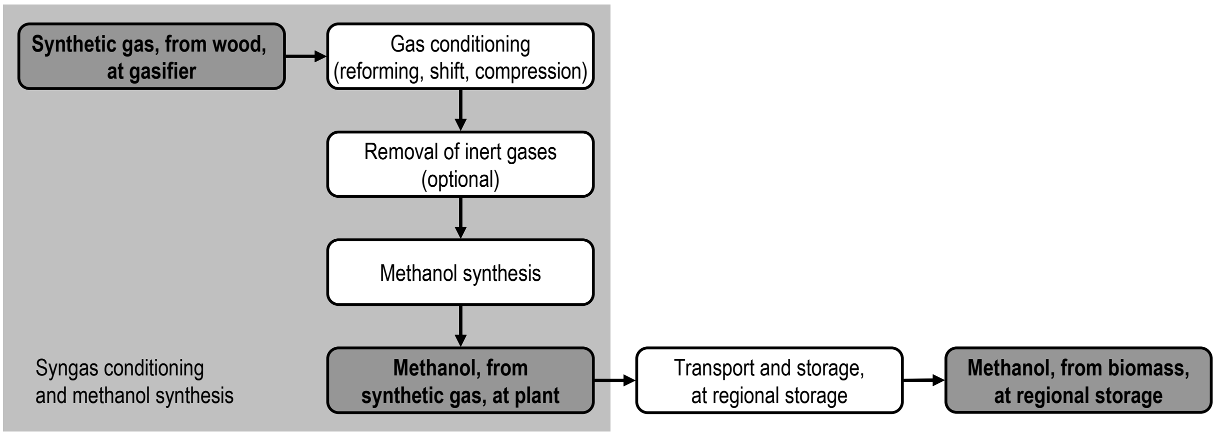


Fig. 18.13 Definition of the system of biomethanol synthesis as described in this chapter.

The syngas resulting from the gasification of woody biomass consists mainly of H_2, CO, CO_2 and CH_4 (see Tab. 18.6). Their shares in the syngas can be tailored to the needs of the methanol synthesis through various processes including methane reforming (converts CH_4 with steam to CO and H_2), shift reactions (adjusts the H_2:CO ratio by converting CO with steam to H_2 and CO_2) and CO_2 removal (reduces the amount of inert gases for the methanol synthesis). The present paragraph is divided into two sub-paragraphs, namely syngas processing and conditioning on the one hand, and actual methanol synthesis on the other hand.

Syngas processing and conditioning

The syngas can contain a considerable amount of methane and other light hydrocarbons, representing a significant part or the heating value of the gas (see Tab. 18.6). In the presence of a suitable catalyst, CH_4, tars and light hydrocarbons are reformed into CO and H_2 at high temperature. The highly endothermic process takes place over a nickel-based catalyst, through the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$C_2H_4 + H_2O \rightarrow 2CO + 4H_2$$

$$C_2H_6 + H_2O \rightarrow 2CO + 5H_2$$

Steam reforming (SMR) is the most widespread method and uses steam as the conversion reactant and to prevent carbon formation during operation. A high steam-to-carbon ratio favours a higher H2:CO ratio and thus a higher methanol production efficiency. Typical steam-to-carbon ratio is 3:1, while typical temperatures range from 850 to 1000°C. The inlet steam is heated by the outlet stream up to near reformer temperature to match reformer heat demand and supply. Electrical power use of an SMR is typically 21 kWh/Nm^3 of H_2 produced (Hamelinck 2001). Catalysts constraint to sulphur is as low as 0.25 ppm. The lifetime of catalysts ranges from 3 years to 5 years (van Dijk 1995; NREL 2003; Hamelinck 2001).

Another option, autothermal reforming (ATR) combines partial oxidation in the first part of the reactor with steam reforming in the second part, thereby optimally integrating the heat flows, but at the expense of increased equipment cost. In this project, conventional steam reforming (SMR) is preferred to ATR.

Since the H_2:CO ratio of the syngas (about 0.8-0.9:1 on a molar basis) is low compared to the 'ideal' ratio for methanol synthesis (approximately 2:1), a water gas shift (WGS) reaction is a conducted to shift the energy value of the CO to H_2. The gas-shift reaction can be represented as follows:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

This reaction is exothermic and proceeds nearly to completion at low temperatures. Modern catalysts are active as low as 200-400°C (Katofsky 1993) and very selective, so that all gases except those involved in the reaction are inert. The shift reaction is conventionally carried out in a single CO-shift reactor operating at medium temperature (210°C). In the case of methanol synthesis, the syngas is shifted partially to a suitable H2:CO ratio, which allows to even operate at higher temperature and save process heat. If in theory, the steam:CO ratio could be 2:1, in practice, extra steam is added to prevent coking the ratio is set to 3:1. Depending on the operating temperature, catalysts will range from iron oxide-chromium oxide to zinc oxide-copper oxide, and are expected to last for 3-5 years (NREL 2003; Hamelinck 2003).

Depending on the composition of the syngas, the water gas shift can be used in combination with a CO_2 removal step. In order to get the ratio (H_2-CO_2):(CO+CO_2) to the value desired for methanol synthesis, part of the carbon oxides could have to be removed, which can be done by partially scrubbing out the carbon dioxide. For this purpose, various physical and chemical processes are available. Chemical absorption using amines is the most conventional and commercially best proven option. In this process, CO_2 chemically binds to the absorbent at relatively low temperature and is later stripped off by hot steam. The heat consumption of the process lays in between 3.6 and 4.2 MJ per kg of CO_2 removed (Farla 1995). The electric power consumption for flue gas blowers is 48 kWh/t CO_2 removed (Hamelinck 2001).

Methanol production

Methanol is produced by the hydrogenation of carbon oxides over a suitable catalyst (copper oxide, zinc oxide, aluminium oxide or chromium oxide). The chemical reactions can be written as follows:

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta H = -90.6\,kJ/mol$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \qquad \Delta H = -46.7\,kJ/mol$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41.5\,kJ/mol$$

The first reaction is the primary methanol synthesis reaction. A small amount of CO_2 in the feed (2-

10%) acts as a promoter of this reaction and helps to maintain the catalyst activity. The stoechiometry of both reactions is satisfied when the (H_2-CO_2):(CO+CO_2) ratio is 2.03. Because H_2 builds up in the recycle loop, the actual ratio is typically 3-4:1 Only a portion of the CO in the feed gas is converted to methanol in one pass through the reactor, due to the low temperature at which the catalyst operates. The unreacted gas is recycled at a ratio of 2.3-6:1.

The synthesis reactions are exothermic and give a net decrease in molar volume. Therefore, the equilibrium is favoured by high pressure and low temperature. During production, heat is released and has to be removed to maintain optimum catalyst life and reaction rate. The catalyst deactivates primarily because of loss of active copper due to physical blockage of the active sites by large by-product molecules, poisoning by halogens or sulphur in the synthesis gas, and sintering of the copper crystallites into larger crystals (NREL 2003; Hamelinck 2001).

Methanol synthesis can be divided into two main technologies, namely conventional gas phase fixed bed reactors on the one hand, and the so-called liquid phase 'slurry technology' on the other hand, the latter being under development while the first is a long proven technology used in the production of methanol from natural gas. The two technologies are here briefly described.

Conventional methanol reactors use fixed beds of catalyst pellets and operate in the gas phase. Two reactor types predominate in plants built after 1970. The ICI low-pressure process (see Fig. 18.14a) is an adiabatic reactor with cold unreacted gas injected between the catalyst beds. The subsequent heating and cooling leads to an inherent inefficiency, but the reactor is very reliable and therefore still predominant. The Lurgi system (see Fig. 18.14b), with the catalyst loaded into tubes and a cooling medium circulating on the outside of the tubes, allows near-isothermal operation. The conversion to methanol is limited by equilibrium considerations and the high temperature sensitivity of the catalyst. Temperature moderation is achieved by recycling large amounts of hydrogen rich gas, utilising the higher heat capacity of H_2 gas and the higher gas velocities to enhance the heat transfer. Typically a gas phase reactor is limited to about 16% CO gas in the inlet to the reactor, in order to limit the conversion per pass and avoid excess heating.

Processes under development at present focus on shifting the equilibrium towards the product side to achieve higher conversion per pass. Examples are liquid phase methanol processes where reactants, product, and catalyst are suspended in a liquid. In liquid phase processes, heat transfer between the solid catalyst and the liquid phase is highly efficient, thereby allowing high conversions per pass without loss of catalyst activity. Different reactor types are possible for liquid phase methanol production, such as a fluidized beds and monolithic reactors. The slurry bubble column reactor of the LPMEOH process (registered trademark of Air Products and Chemicals, Inc., see Fig. 18.14c) was invented in the late 1970's and further developed and demonstrated in the 1980's. Reactants from the gas bubbles dissolve in the liquid and diffuse to the catalyst surface, where they react. The products then diffuse through the liquid back to the gas phase. Heat is removed by generating steam in an internal tubular heat exchanger. Preceding liquid phase methanol synthesis, the water gas shift is not necessary since the reaction is flexible with respect to the gas composition.

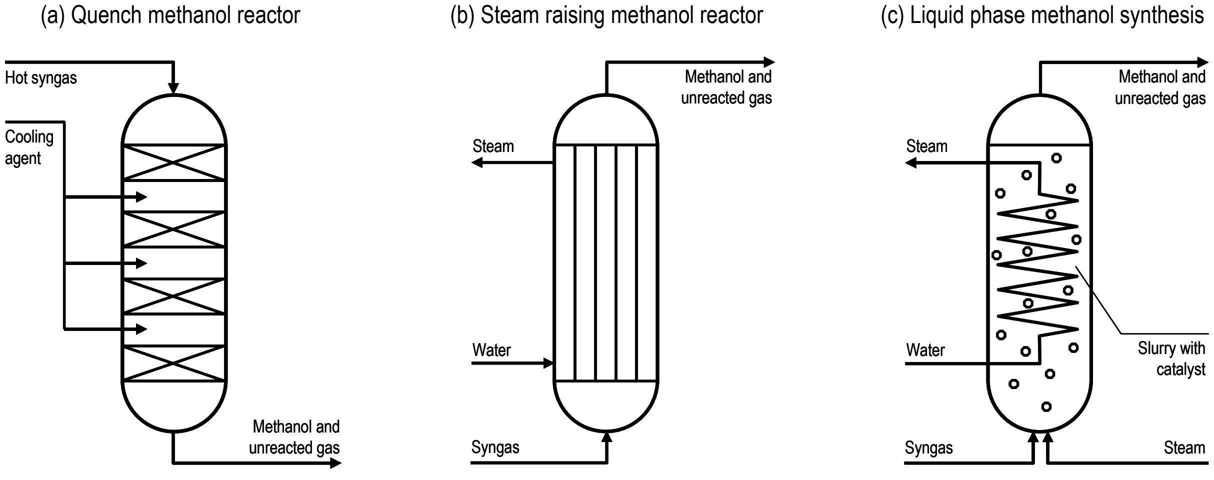


Fig. 18.14 Gas phase (a, b) and liquid phase (c) methanol reactors. Adapted from (Hamelinck 2001).

Conversion per pass depends on reaction conditions, catalyst, solvent and space velocity. Experimental results show 15-40% conversion for CO rich gases and 40-70% for balanced and H_2 rich gases. Computation models predict future CO conversions of over 90 %, up to 97 % respectively (NREL 2003; Hamelinck 2001). Researchers at the Brookhaven National Laboratory have implemented a low temperature (active as low as 100°C) catalyst that can convert 90% of the CO in one pass (Katofsky 1993). With steam addition the reaction mixture becomes balanced through the water gas shift reaction, so that the initial hydrogen to carbon monoxide ratio is allowed to vary from 0.4 to 5.6 without a negative effect on performance.

Heat integration and co-generation of electricity

When designing a methanol facility, various production schemes may be envisaged, typically all-methanol and electricity-methanol co-production. Unconverted fuel gases which remain after the synthesis of methanol production section can indeed still contain a significant amount of chemical energy, and although they have a much lower heating value than natural gas, these gas streams may be combusted in a gas turbine for power generation. When the heating value of the gas stream does not allow stable combustion in a gas turbine or when co-generation of electricity is not desired, the gas is fired in a boiler to raise process steam. In the present case, no co-generation of electricity is considered and the gas is fed to the boiler.

As it has been indicated all along the present section, heat (in the form of steam) is supplied at several points in the production process. It is of great importance for the process efficiency that supply and demand are carefully matched.

There usually is a supply of heat after the gasifier and reformer, where the gas streams are cooled prior to gas cleaning or compression. Furthermore, heat may be recovered from flue gas from the boiler. There generally is a heat demand for the gas stream entering the reformer, and a steam demand for drying, for the gasifier, the reformer and the shift reactor.

18.5.4 LCI of 'Methanol, from synthetic gas, at plant'

The process 'methanol, from synthetic gas, at plant' includes raw materials (incl. synthesis gas, processing energy, estimate on catalyst use, use of water for steam reforming) and synthesis of methanol. The data in Tab. 18.18 presents the methanol yield from syngas according to various literature sources.

Tab. 18.18 Methanol yield from syngas according to various literature sources.

Source		ICCEPT 2003	Mehlin 2003	Rollins 2002			Hamelinck 2001	Average
Biomass	t_{DM}	100.0	100.0	100.0	100.0	100.0	100.0	**100**
Methanol	t	43.2	50.8	49.7	48.1	48.8	42.3	**47.2**
Yield	t/t_{DM}	0.432	0.508	0.497	0.481	0.488	0.423	**0.472**

The overall methanol yield (expressed in tons of methanol produced per ton of dry matter biomass) is 0.472, which corresponds to 0.195 kg methanol per Nm^3 of syngas. In other words, the production of 1 kg methanol consumes 5.128 Nm^3 of syngas.

Due to a significant lack of data (production of methanol from bio-syngas has hardly reached pilot scale development), the process is strongly based on the process 'methanol, at plant' describing the production of methanol from natural gas (Althaus 2004). It is often mentioned in the literature that the processes of methanol from natural gas and methanol from syngas are very similar, and therefore, some of the process stages are considered to be identical. For instance, the supply of catalysts, the demand for cooling and process water, water emissions and most of air emissions are all reproduced from the 'methanol from natural gas' process. A few descriptive elements are here copied from (Althaus 2004) for a minimum understanding of the data. However, for further details, the reader should refer to the original document.

Water requirements include process water make-up and cooling water make-up. Process water make-up is taken as 0.85 kg/kg of methanol and is characterised as 'water, deionised, at plant'. Cooling water make-up is given as 8.16 kg/kg of methanol, of which 1.80 kg (i.e. 3% of the 60 kg of the required circulating water) are evaporated, and 6.36 kg are discharged from the cooling system.

As far as water emissions are concerned, the only regular waste product is the bottoms residue obtained after distillation of pure methanol. It contains water, methanol, ethanol, higher alcohols, other oxygen-containing organic compounds, and variable amounts of paraffin. At the bottom of the refining column, 0.2 kg of polluted wastewater per kg of methanol is discharged. This wastewater is sent to a biological treatment unit. The waterborne emissions are assumed as reported in (Althaus 2004), as indicated in Tab. 18.19.

Due to the fact that some chemicals are used to treat the cooling water to prevent corrosion, sealing and fouling, some pollution within the cooling water discharge is also considered (see Tab. 18.19). The pollution is assumed to be equal to the minimum requirements for the cooling water discharge, as described by IPPC.

Tab. 18.19 Emissions to water per kg of methanol produced (Althaus 2004).

Substance	Emissions from waste water		Emissions from cooling water	
	Flowrate kg/kg methanol	Concentration g/m^3	Flowrate kg/kg methanol	Concentration g/m^3
COD	3.00E-03	1.50	1.90E-04	30.00
BOD	1.80E-04	0.90	-	-
DOC, TOC	1.80E-04	0.50	6.00E-05	10.00
AOX	-	-	1.00E-06	0.15
Phosphorous	-	-	1.00E-05	1.50
Formaldehyde, CH_2O	1.00E-04	0.50	-	-
Methanol, CH_3OH	3.00E-05	0.13	-	-
Phenol, C_6H_6	1.00E-05	0.07	-	-
Suspended solids	2.00E-05	0.00	-	-
Chloride, Cl	-	0.10	2.00E-06	0.30

After the stages of reforming and water gas shift, the syngas in both processes should really be of the same nature, with an ideal H_2:CO ratio of about 2.2-2.3 and some CO_2. For instance, methanol emissions to the atmosphere, like NO_x resulting from the combustion in the furnace of the remaining hydrogen, are taken identical to those of methanol from natural gas. Some of the data, however, is considered to be specific to methanol from biomass, including:

- the supply of energy within the whole methanol plant, including in particular (1) the energy consumed for the compression of the syngas before steam reforming (indeed, the syngas leaving the gasification plant is at atmospheric pressure, whereas the synthesis of methanol requires high pressure), and (2) the energy demand for the steam reforming process itself,
- the volumes of waste streams to the process,
- the waste heat released to the atmosphere,
- the emissions to air, based on the heat supply strategy and the composition of the syngas.

Like in the case of syngas production, the heat is considered to be supplied by syngas combustion. According to (Althaus 2004), the overall heat demand for methanol synthesis from natural gas amounts to 7.7/1.05 MJ/kg methanol. If we consider the specific additional amount of heat required by the syngas-to-methanol process, the overall heat demand is 9.527 MJ/kg methanol. Considering an efficiency of the syngas boiler of 90%, the consumption of syngas (5.3 MJ/Nm^3) for heat production is 1.997 Nm^3/kg methanol, which gives a total syngas consumption of 7.126 Nm^3/kg methanol.

According to (Williams 1995), the electricity use for the overall process of methanol production from biomass (in the case of atmospheric gasification) amounts to 35.4 kWh/GJ of methanol of which 61% is produced internally from the waste heat and 39% is coming from external sources. Overall, the net consumption of electricity is 0.277 kWh/kg methanol.

As far as emissions to air are considered, the same hypotheses as in the gasification process are considered for syngas combustion emissions (see paragraph 18.4.6). As all the sulphur is eliminated from the syngas prior to methanol synthesis, SO_x emissions are considered to be zero. NO_x and methanol emissions are considered to be equal to those in the process of methanol from natural gas.

The carbon ending up in the waste streams and effluents eventually ends up as CO_2 downstream of the methanol process. The amount of carbon is determined in order to close the overall carbon balance of the process, given the carbon content of inputs and outputs. Direct CO_2 emissions amount to 2.491 kg CO_2/kg of methanol, and are considered to be emitted to air, high population density.

The calculation of the amount of effluents is based on the overall mass balance of the process. Effluents amount to 0.00532 m^3/kg of methanol.

Waste heat consists of two main components, i.e. the waste heat relating (1) to the synthesis of methanol (10.586 MJ/kg methanol) and (2) to the combustion of syngas for heat supply (4.480 MJ/kg methanol). Additionally, all electricity consumption is generating waste heat of the same amount of energy. Waste heat is emitted to air, high population density.

The unit process raw data of ‘methanol, from synthetic gas, at plant’ is indicated in Tab. 18.21.

Tab. 18.20 Unit process data of the datasets 'methanol, from synthetic gas, at plant'.

	Name	Location	InfrastructureProcess	Unit	methanol, from synthetic gas, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				kg			
product	methanol, from synthetic gas, at plant	CH	0	kg	1.00E+0			
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	8.16E-3	1	1.59	(2,3,3,3,4,5); Data dependent on technology, average used
technosphere	aluminium oxide, at plant	RER	0	kg	2.40E-4	1	2.16	(4,5,3,3,5,5); Adapted from 'methanol (from natural gas), at plant'
	copper oxide, at plant	RER	0	kg	9.00E-5	1	2.16	
	molybdenum, at regional storage	RER	0	kg	1.00E-5	1	2.16	
	nickel, 99.5%, at plant	GLO	0	kg	2.00E-5	1	2.16	
	zinc for coating, at regional storage	RER	0	kg	3.00E-5	1	2.16	
	methanol plant	GLO	1	unit	3.70E-11	1	3.10	(2,3,1,3,3,5); Calculation
	synthetic gas, production mix, at plant	CH	0	Nm3	7.13E+0	1	1.52	(3,2,1,2,4,2); Data derived from literature survey (>20 sources) 2000-2005
	electricity, medium voltage, at grid	CH	0	kWh	2.77E-1	1	1.65	(4,4,3,2,4,5); Data strongly dependent on technology, data from one source
	water, deionised, at plant	CH	0	kg	8.50E-1	1	1.53	(3,3,2,3,4,3); Data dependent on technology
	transport, freight, rail	CH	0	tkm	1.38E-4	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.95E-2	1	2.09	
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	5.32E-3	1	1.56	(5,5,na,na,na,na); Estimated, to close mass balance
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	2.76E+0	1	1.53	(3,3,2,3,4,3); Calculation, to close carbon balance
	Acetaldehyde	-	-	kg	3.10E-9	1	1.80	(3,3,2,3,4,3); Calculation, from syngas composition and natural gas combustion
	Acetic acid	-	-	kg	4.65E-7	1	1.80	
	Benzene	-	-	kg	1.24E-6	1	1.80	
	Benzo(a)pyrene	-	-	kg	3.10E-11	1	3.25	
	Butane	-	-	kg	2.17E-6	1	1.80	
	Carbon monoxide, biogenic	-	-	kg	6.51E-6	1	5.28	
	Dinitrogen monoxide	-	-	kg	3.10E-7	1	1.80	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	9.30E-17	1	3.25	
	Formaldehyde	-	-	kg	3.10E-7	1	1.80	
	Mercury	-	-	kg	9.30E-11	1	5.28	
	Methane, biogenic	-	-	kg	6.20E-6	1	1.80	
	Nitrogen oxides	-	-	kg	2.06E-4	1	1.80	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	3.10E-8	1	3.25	
	Particulates, < 2.5 um	-	-	kg	6.20E-7	1	3.25	
	Pentane	-	-	kg	3.72E-6	1	1.80	
	Propane	-	-	kg	6.20E-7	1	1.80	
	Propionic acid	-	-	kg	6.20E-8	1	1.80	
	Sulfur dioxide	-	-	kg	1.71E-6	1	1.53	
	Toluene	-	-	kg	6.20E-7	1	1.80	
	Methanol	-	-	kg	5.30E-4	1	1.53	(2,4,1,3,1,3); Based on ecoinvent Guidelines
	Heat, waste	-	-	MJ	1.61E+1	1	1.30	(1,1,1,2,3,5); Based on ecoinvent Guidelines and energy balance closure
emission water, river	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	1.00E-6	1	1.89	(3,5,2,3,4,5); Adapted from 'methanol (from natural gas), at plant'
	BOD5, Biological Oxygen Demand	-	-	kg	1.80E-4	1	1.89	
	Chloride	-	-	kg	2.00E-6	1	3.33	
	COD, Chemical Oxygen Demand	-	-	kg	4.90E-4	1	1.89	
	DOC, Dissolved Organic Carbon	-	-	kg	2.40E-4	1	1.89	
	Formaldehyde	-	-	kg	1.00E-4	1	3.33	
	Methanol	-	-	kg	3.00E-5	1	3.33	
	Phenol	-	-	kg	1.00E-5	1	3.33	
	Phosphorus	-	-	kg	1.00E-5	1	1.89	
	Suspended solids, unspecified	-	-	kg	2.00E-5	1	1.89	
	TOC, Total Organic Carbon	-	-	kg	2.40E-4	1	1.89	

In conclusion, it is worth mentioning that wood gasification and methanol production from syngas can achieve significant energy savings by a good energy integration of the two processes, which is not the case here. Methanol synthesis, indeed, is realized by largely exothermic reactions (see paragraph 18.5.3), which generate heat at a temperature too low for most heat demand on the methanol side, but which would be profitable on the gasification side, for the drying stage for example. Such integrations are not considered here.

18.5.5 LCI of 'Methanol, from biomass, at regional storage'

The unit process 'methanol, from biomass, at regional storage' envisages the transport of methanol (for use as a vehicle fuel and produced from synthetic gas) from the methanol plant to a regional service station (incl. storage, treatment of effluents) and distribution to the end-user. For reasons of consistency with other datasets relating to the distribution of fuels (e.g. gasoline, diesel), the present dataset is based on the existing dataset 'petrol, unleaded, at regional storage' (Jungbluth 2004). Fugitive emissions are adapted to the specific nature of methanol.

Due to a lack of information about actual distances and the very little development of the use of methanol as a vehicle fuel so far, standard distances are used, in accordance with the recommendations in (ecoinvent Centre 2004), i.e. 100 km by train and 150 km by 28t lorry.

The unit process raw data is indicated in Tab. 18.21.

Tab. 18.21 Unit process data of the dataset 'methanol, from biomass, at regional storage'.

	Name	Location	InfrastructureProcess	Unit	methanol, from biomass, at regional storage	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				kg			
product	methanol, from biomass, at regional storage	CH	0	kg	1.00E+0			
technosphere	electricity, low voltage, at grid	CH	0	kWh	6.70E-3	1	1.14	(2,4,1,3,1,3); Environmental report
	methanol, from synthetic gas, at plant	CH	0	kg	1.00E+0	1	1.52	(3,2,1,2,4,2); Data derived from literature survey (>20 sources) 2000-2005
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.21E-4	1	1.14	(2,4,1,3,1,3); Environmental report
	transport, freight, rail	CH	0	tkm	1.00E-1	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	1.50E-1	1	2.09	
	regional distribution, oil products	RER	1	unit	2.62E-10	1	3.01	(3,na,1,3,1,na); Calculation
	tap water, at user	CH	0	kg	6.89E-4	1	1.56	(5,5,1,2,1,na); Environmental report
	disposal, separator sludge, 90% water, to hazardous waste incineration	CH	0	kg	1.68E-4	1	1.17	(2,4,3,3,1,3); Environmental report and literature
	disposal, municipal solid waste, 22.9% water, to sanitary landfill	CH	0	kg	6.27E-6	1	1.14	(2,4,1,3,1,3); Environmental report
	treatment, rainwater mineral oil storage, to wastewater treatment, class 2	CH	0	m3	7.50E-5	1	1.32	(4,5,3,3,1,na); Rainwater with pollutants
	treatment, sewage, to wastewater treatment, class 2	CH	0	m3	6.89E-7	1	1.14	(2,4,1,3,1,3); Used water
emission air, high population density	Methanol	-	-	kg	5.00E-4	1	1.53	(2,4,1,3,1,3); Based on ecoinvent Guidelines
	Heat, waste	-	-	MJ	2.41E-2	1	1.30	(1,1,1,2,3,5); Based on ecoinvent Guidelines and energy balance closure

18.6 Methane 96% vol. from syngas

18.6.1 Characterisation of methane from syngas

The present section aims at characterising the most significant physical and chemical characteristics of methane (96% vol.) from synthetic gas, such as the density, energy content or cetane index.

Methane 96% (CH_4, CAS-No. 74-82-8) can be apparented to natural gas in terms of its physical and chemical properties. It is used in many industrial applications for heat and power supply, or as a transportation fuel. It is also used as the main raw material in numerous manufacturing processes, including fertilisers, etc.

The density of methane is found to be of the order of 0.752 kg/Nm^3, while the lower and higher heating values are respectively 34.4 and 38.1 MJ/Nm^3. The main characteristics of methane 96% are given in Tab. 18.22 below. The data is taken from 'methane, 96 vol.-%, from biogas, at plant'.

Tab. 18.22 Main characteristics of methane (96% vol.) from syngas.

		Methane, 96 vol.-%, from synthetic gas	
basic unit in database		**kg**	**Nm3**
Lower heating value (Hu)	MJ/kg	45.8	34.4
Upper heating value (Ho)	MJ/kg	50.7	38.1
Density 20°C	kg/l	0.00075	0.00075
Density 20°C	kg/m^3	0.752	0.752
Oxygen	kg/kg	0.057	0.043
Carbon, fossil	kg/kg	0.000	0.000
Carbon, biogen	kg/kg	0.698	0.525
Hydrogen	kg/kg	0.228	0.171
Sulphur	ppm	6.651	6.651
CO_2 Factor	kg/MJ (Hu)	0.0559	0.0559
CO_2 Factor	kg/kg	2.56	1.92
Formula		CH_4 (96%)	CH_4 (96%)
CAS		74-82-8	74-82-8
Source		*methane, 96 vol.-%, from biogas*	*methane, 96 vol.-%, from biogas*

18.6.2 Applications and use of methane from syngas

Methane, whether it be produced from syngas by methanation, extracted directly from the ground, derived from fermentation biogaz, or any other process chain, is always methane and is suited for any application appropriate to natural gas (i.e. heat and power applications or transportation fuel). Applications and uses of natural gas are described thoroughly in other ecoinvent reports and therefore are not described again here. The reader is advised to refer to the corresponding ecoinvent reports for further details.

18.6.3 System definition

Methane (96% vol.) can be obtained from syngas by methanation. The two processes (gasification and methanation), however, are intimately integrated. Operational paramters in the gasification stage (incl. temperature, pressure, gasification technology, syngas cleaning processes, catalysts, bed material, etc.) offer some degrees of freedom with respect to syngas composition, and indeed are often optimised according to the subsequent stage or use of the syngas (in this case methanation). The combination of gasification and methanation processes is therefore considered as a whole in this chapter.

The system described in this paragraph includes the production of methane (96% vol.) from wood chips (see Fig. 18.15). In order to ensure as much coherence as possible with the the previous datasets (see section 18.4), the same feed is considered in the present process.

Like previously, the wood chips supplied to the gasification plant consist of a mixture of wood chips from forest management, wood chips from the wood industry and wood chips from waste demolition and urban wood. The respective shares of each feedstock are here defined in accordance with the data presented in Tab. 18.2, resulting in the following data:

- wood chips, mixed, u=120%, at forest: 64% (corresponding to 3.2/5)
- wood chips, mixed, from industry, u=40%, at plant: 22% (corresponding to 1.1/5)
- waste wood chips, mixed, from industry, u=40%, at plant: 14% (corresponding to 0.7/5)

The entire system described here is based on Research & Development (R&D) activities of the Paul Scherrer Institut (PSI, Switzerland), in collaboration with the operators of the gasification pilot plant in Güssing (Austria). The gasification technology employed at Güssing is of the FICFB or BCL type (see Fig. 18.6c), consisting in two fluidized bed reactors (a gasification reactor and a combustion reactor) operating in parallel.

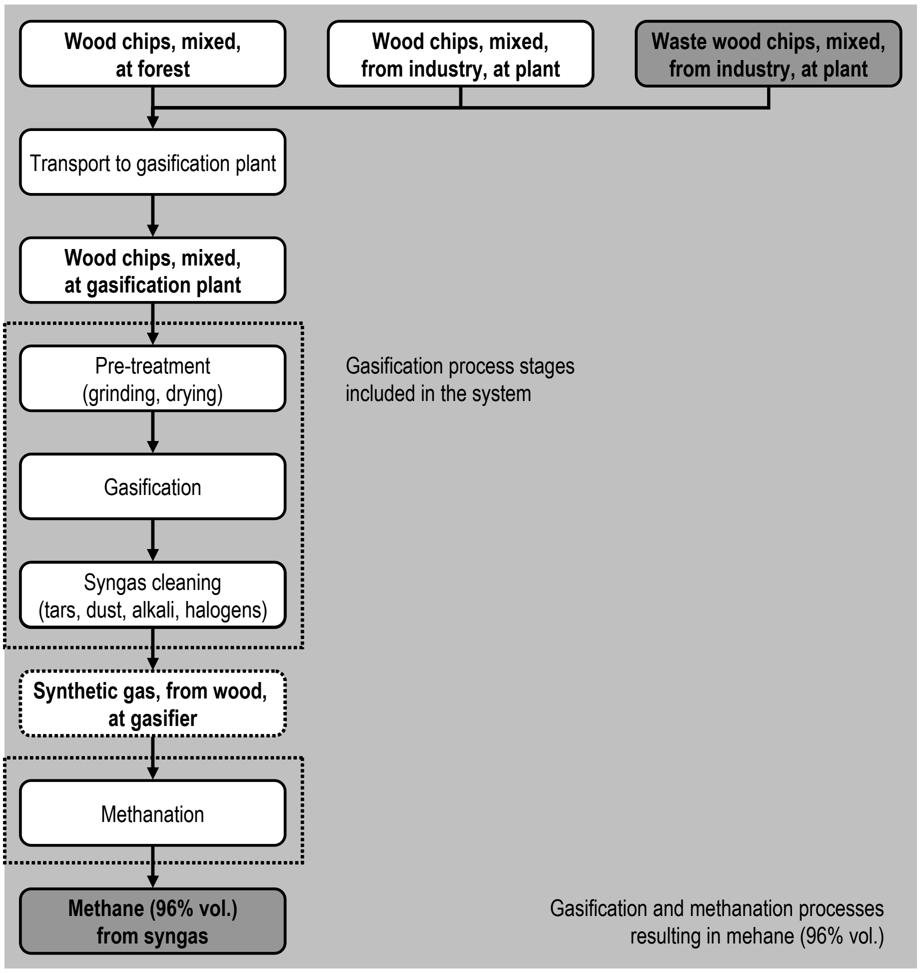


Fig. 18.15 Limits of the gasification processes covered in this chapter.

The description of the process presented below is based mainly on a document from the PSI, namely (Felder 2004). Unless stated otherwise, the information and data in this section is from this reference. Process data (incl. efficiency, operational use oenergy and resources but also emissions) are assembled based on measurements at the CHP pilot plant in Güssing (Austria) for the gasification part and results from the actual PSI research for the methanation part. They represent the best estimate possible for an operational plant at present (Felder 2004).

As mentioned before, the overall process consists of two major stages, i.e. gasification and methanation. The two stages are now briefly described.

Gasification

Gasification is performed using the FICFB principle (Fast Internally Circulating Fluidized Bed (see Fig. 18.6c and Fig. 18.16). In the right part of the reactor (gazification zone), the biomass is gasified. The unoxidised component of the feed is transported to the left part (combustion zone) together with bed material (olivine), where it is burnt completely. The heat released thereby is transported with the circulating bed material back to the right part where it keeps up the gasification process. The gasification zone is fluidized with steam, and the combustion part with air. As the gas streams are removed separately, this leads to a low-nitrogen and low-tar syngas (product gas).

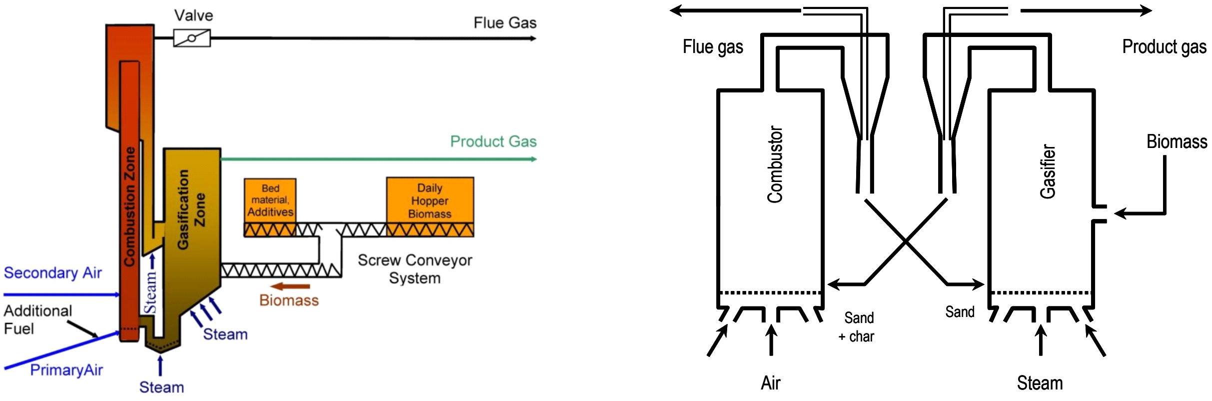


Fig. 18.16 Schematic representation of FICFB types of gasifiers (left: adapted from www.ficfb.at).

The cold gas efficiency (see 18.4.4) of the gasification process depends mainly on the temperature and the water content of the biomass. At a gasification temperature of 850°C and a water content of 15% (i.e. u=18%), the cold gas efficiency is 73%. Lowering the temperature and drying the wood chips increase the efficiency. For the calculations, wood chips are supposed to be dried down to u=18% and an efficiency of 73% for the gasification part is assumed.

In such conditions, the gasification in Güssing delivers a product gas with about 39% (vol.) H_2, 20% CO_2, 27% CO and 14% CH_4 on a dry basis, and a calorific value of 14 MJ/Nm^3. The composition and main properties of the resulting syngas (dry basis) are given in Tab. 18.23.

Tab. 18.23 Main characteristics of syngas at the gasification plant in Güssing (Felder 2004).

basic unit in database		Syngas (dry basis) Nm3
Lower heating value (Hu)	MJ/Nm^3	13.989
Upper heating value (Ho)	MJ/Nm3	-
Density 20°C	kg/Nm^3	1.501
Oxygen	kg/kg	0.553
Carbon, fossil	kg/kg	0.000
Carbon, biogen	kg/kg	0.378
Hydrogen	kg/kg	0.069
Nitrogen	kg/kg	0.000
Molar composition (dry basis)		
H_2	%mol	39.0
CO	%mol	27.0
CO_2	%mol	20.0
CH_4	%mol	14.0
Weight composition (dry basis)		
H_2	%wt	4.0
CO	%wt	39.0
CO_2	%wt	45.4
CH4	%wt	11.6

The syngas also contains undesired traces of tar (1.5-2.5 g/Nm^3), ammonium (about 1’000 ppm), dust (10-20 g/Nm^3) and traces of H_2S (about 50-150 ppm). These traces are removed by cleaning processes from the syngas and put back into the gasifier. Rape methyl ester (RME) is used for tar removal. H_2S is eliminated by filtering through a ZnO bed, which absorbs the sulphur to form ZnS. The ZnO can be regenerated by a reaction with oxygen contained in air. Thereby, SO_2 is formed which can be converted into sulphuric acid, sulphur or calcium sulphate. In this study we assume that the sulphur reacts with calcium carbonate to give gypsum (calcium sulphate), which is eventually deposited in a sanitary landfill.

In the gasifier, olivine is used as bed material (MgFe-silicate), while Sorbalit (a mixture of limestone and charcoal) is used as pre-coating material. In order to start the gasification plant, an oil burner is used, fueled with light fuel oil or RME depending usually on which is cheaper. Such operation is done every 2'000 h at present, in Güssing.

Before the subsequent methanation process, the gas is transported further by a blower. It is compressed to about 2 bar, for which an energy amount of about 1.620 kWh/$GJ_{biomass}$ is used.

Methanation

During methanation, the C-containing substances are transformed into methane as much as possible. CO reacts with H_2 to methane and water. The CH_4 gain rises with increasing pressure and dropping temperature. The resulting gas is typically composed of 97.3% (vol.) CH_4, 2.6% CO_2 and 0.1% H_2O.

A typical efficiency (MJ_{out}/MJ_{in}) of 76.5% is assumed for the process.

A catalyst consisting of 50% (wt.) aluminium oxide and 50% nickel is used during the methanation process. The amount required is 100 g and has to be replaced about every 5'000 h. Carbon deposition during the process is not included in the modelling.

Most of the water in the resulting gas is condensed, and can be used for the production of the process steam. Residual water is removed using a silica-gel, which can be regenerated. Carbon dioxide is removed by a pressure-swing-adsorption (PSA). This is done by a molecular sieve (zeolith), which also can be regenerated. The energy use for regeneration of the gel and the molecular sieve is not taken into account in the modelling.

After the methanation, the gas is compressed to the gas network pressure (30-70 bar).

The overall gross efficiency of the process is of the order of 56%, as the product of the efficiencies of the gasification (73%) and the methanation (76.5%).

18.6.4 LCI of 'Methane, 96 vol.-%, from synthetic gas, wood, at plant'

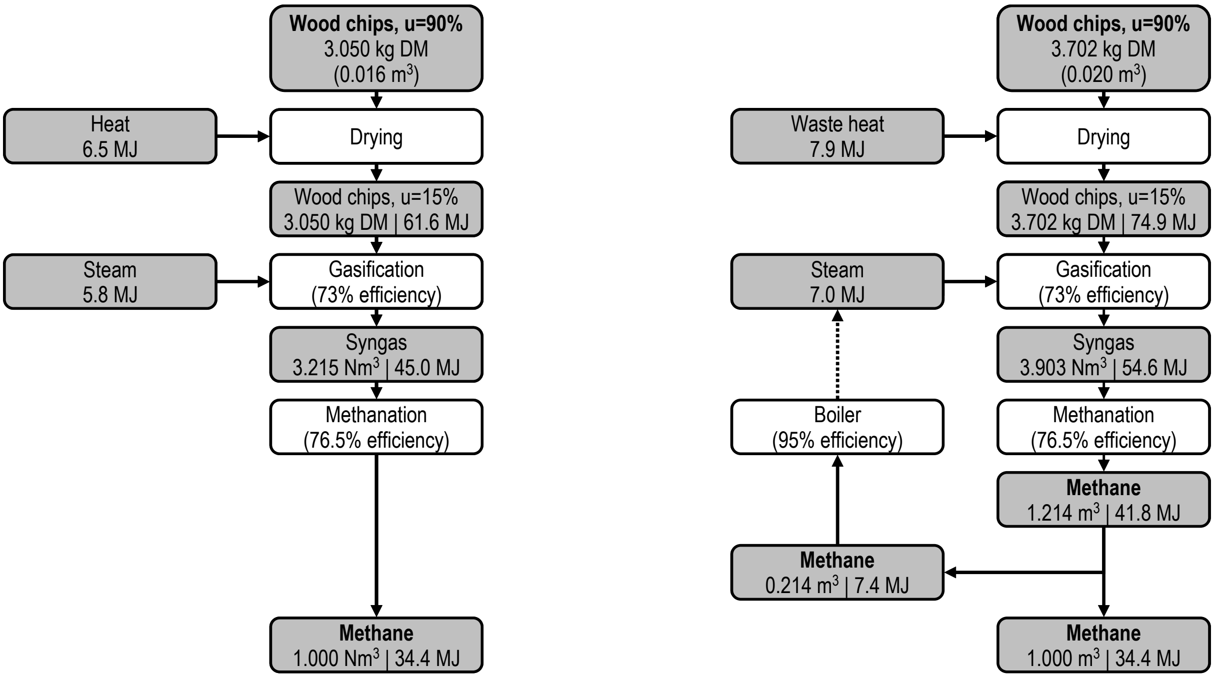
The inventory of 'methane, 96 vol.-%, from synthetic gas, wood, at plant' is compiled using the data provided in (Felder 2004) as well as own calculations based on the previous datasets relating to gasification (see paragraphs 18.4.6 and 18.4.7).

As described before, the process 'methane, 96 vol.-%, from synthetic gas, wood, at plant' includes the production of methane by gasification of mixed wood chips, and methanation of the resulting syngas, including initial drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), as well as gas cleaning and conditioning. Composition of the resulting gas (methane) is 97.3% (% mol.) CH_4, 2.6% CO_2 and 0.1% H_2O. The energy content is 34.4 MJ/Nm^3. The inventory refers to the production of 1 Nm^3 of methane.

It is assumed in this inventory that all the heat required within the process (including gasification and methanation), is supplied by burning some of the resulting methane to raise steam with an efficiency of 95%. The S/B ratio (see paragraph 18.4.4) in the gasification process is considered to be 0.630 kg (i.e. 1.890 MJ at 3 MJ/kg) steam per kg DM wood. The amount of heat for drying the chips is taken according to (Hamelinck 2001) and is equal to 2.8 MJ per kg of evaporated water. Theheat for drying though is supplied by waste heat from the processes of gasification and methanation. Therefore, the net heat consumption for the drying stage is considered to be zero. The flow diagrams on Fig. 18.17 show the gross and net efficiencies of the overall process.

The gross and net yields of the process are calculated as follows (see Fig. 18.17):

- gross yield: 0.311 Nm^3 of methane per Nm^3 of syngas (i.e. 0.328 Nm^3 per kg DM wood)
- net yield: 0.256 Nm^3 of methane per Nm^3 of syngas (i.e. 0.270 Nm^3 per kg DM wood)



Gross mass and energy balance

Heat supply through methane combustion

Fig. 18.17 Energy balance and efficiency of the overall process of methane production from wood chips.

As indicated before, the proportions of the different qualities of wood chips are considered to be the same as in previous gasification datasets. Given the net yield of methane (0.270 Nm^3 per kg of DM wood chips), the volumes of wood chips (see Fig. 18.18) per Nm^3 of methane are given as follows:

- 'wood chips, mixed, u=120%, at forest': 1.256×10^{-2} m^3
- 'wood chips, mixed, from industry, u=40%, at plant': 4.318×10^{-3} m^3
- 'waste wood chips, mixed, from industry, u=40%, at plant': 2.748×10^{-3} m^3

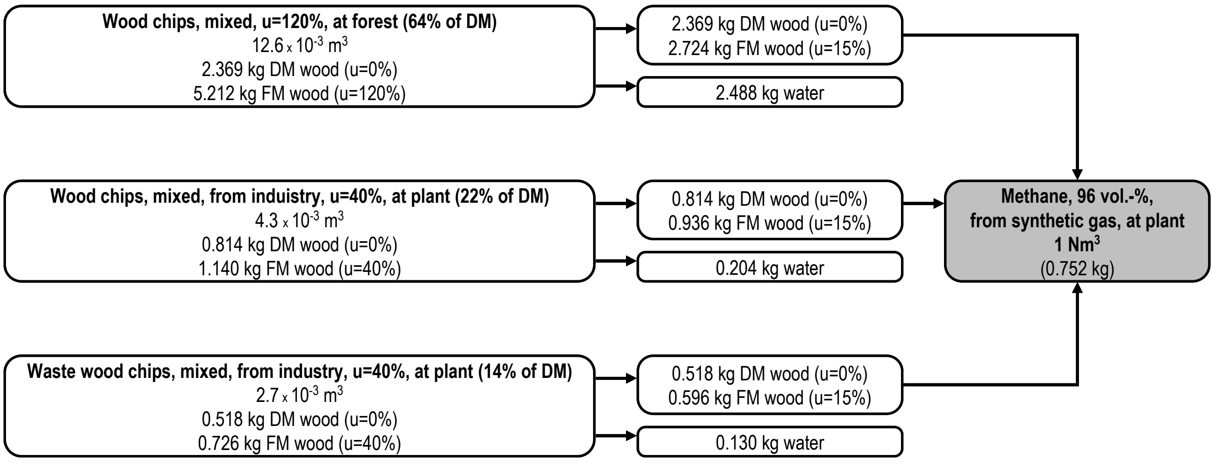


Fig. 18.18 Net yield of methane through FICFB gasification of wood chips and methanation of syngas.

The overall energy efficiency of the methane production process (calculated as the ratio of the energy in methane to the energy in wood chips) is equal to 51.1%.

Transport of feedstock

According to ecoinvent standards for the supply of wood, the transport distance from either the forest or the chopping facility to the gasification plant is taken as 50 km. The transport is performed by 28t truck. Given the net yield of methane and the respective apparent densities of the different qualities of chips (see Tab. 18.4), the effective weight of wood transported to the gasification plant (prior to drying) is equal to:

$12.6 \cdot 10^{-3} \times 414.9 + 4.3 \cdot 10^{-3} \times 264.0 + 2.7 \cdot 10^{-3} \times 264.0 = 7.077$ kg/Nm^3 of methane (net)

Heat requirements

In the first stage of the process, the chips need to be dried down to a moisture content of 10-15% (wt.) water, or u=15% (see Fig. 18.9). The heat is considered to be supplied entirely by waste heat from the gasification and methanation processes. The net consumption of heat is therefore zero. The amount of heat is calculated according to the amount of water to evaporate, and is taken as 2.8 MJ/kg water evaporated (Hamelinck 2001). The amount of heat required for drying purposes is equal to:

$2.8 \times (2.488 + 0.204 + 0.130) = 7.898$ MJ/Nm^3 of methane (net)

As far as the gasification process is concerned, a typical E/R ratio of 0.35 is considered. As noted before, the steam:biomass (S/B) ratio is taken as 0.630. Again, the supply of heat is ensured by the combustion of wood chips. With a value of 3.0 MJ/kg of steam (290°C, 0.1 bar), the amount of heat for the gasification reaction is given by:

$3.0 \times 0.630 / 0.270 = 6.997$ MJ/Nm^3 of methane (net)

The heat required in the gasification process is supposed to be provided by methane combustion (which makes the difference between net and gross yields), with an efficiency of 95%. Emissions due to methane combustion are adapted from the existing process 'natural gas, burned in boiler modulating >100kW'.

Electricity requirements

The drying process also consumes electricity at a rate of 0.025 kWh per kg of water evaporated (i.e. 0.093 kWh/Nm^3 of methane). According to the feed size requirements of the gasifier (30x30x30 mm), further comminution by crushing must be performed. The corresponding electricity consumption is 7.2 kWh per ton of incoming wood (after drying, u=15%), i.e. 0.040 kWh/Nm^3 of methane.

The electricity consumed for the compression of the syngas is given as 0.160 kWh/Nm^3 methane (net), while that consumed in the methanation process (incl. compression of the methane) is 0.513 kWh/Nm^3 of methane (net). Electricity for pumping (16.5 kWh/t_{DM} of wood) and air compression (9 kWh/t_{DM} of wood) is considered as given in (Hamelinck 2001).

The overall requirements of heat and electricity are summarised in Tab. 18.24.

Tab. 18.24 Summary of heat and electricity use in the dataset 'methane, 96 vol.-%, from synthetic gas, wood, at plant'.

Process stages	Heat consumption (MJ/Nm^3 methane)	Electricity consumption (kWh/Nm^3 methane)
Drying	-	9.300E-02
Comminution		4.042E-02
Air compression		4.394E-02
Syngas compression		1.598E-01
Pumping		8.055E-02
Gasification	6.997E+00	
Methanation		5.126E-01
Total (net)	6.997E+00	9.302E-01

Inputs to the process

When not stated in (Felder 2004), inputs relating to gas cleaning operations are adapted from previous gasification datasets (see paragraphs 18.4.6 and 18.4.7) to the composition of the syngas in the present case. For instance, the amount of water contacted with the gas in the wet scrubber is taken as 0.284 kg/kg of dry wood chips (Giordano 1998), i.e. 1.386 kg/Nm^3 of methane. Standard wastewater "quality" is taken into account in the inventory.

The bed material of the gasifier normally consists of olivine, a magnesium-iron silicate. Olivine however does not exist in the ecoinvent database. The process 'silica sand, at plant' is used as a proxy for olivine.

Rape methyl ester is used for tar removal, at a rate of 4 kg/t$_{DM}$ of wood (i.e. 19.3 g/Nm^3 of methane).

Within the scrubbing process, soda (NaOH) is added to get rid of HCl. Similarly, sulphuric acid is added to get rid of NH_3, CS_2 and HCN. The amounts of NaOH and H_2SO_4 are calculated from the typical raw syngas composition as indicated in Tab. 18.11. The consumptions of pure (100%) NaOH and H_2SO_4 are taken respectively as 1.2 times the amount of HCl and 1.2 times the amounts of NH_3, COS and CS_2.

Other inputs are indicated in Tab. 18.25, according to (Felder 2004).

Solid wastes and effluents

The amount of fly ash collected from the gasifier is taken as 9.710 g/kg of DM wood (i.e. 46.1 g/Nm^3 of methane), according to (Felder 2004). Again, it is considered that 60% of the fly ash is disposed of in municipal incineration and 40% is disposed of in sanitary landfill.

Other outputs are indicated in Tab. 18.25, according to (Felder 2004).

Tab. 18.25 Summary of material inputs and outputs of 'methane, 96 vol.-%, from synthetic gas, wood, at plant'.

Inputs/Outputs	Unit	Quantity per t_{DM} of wood	Quantity per Nm^3 of methane (net)
Inputs			
Water	kg	2.840E+02	1.386E+00
Bed material (silica sand)	kg	9.500E+00	4.638E-02
Rape methyl ester	kg	3.950E+00	1.928E-02
Light fuel oil	MJ	1.656E-01	8.085E-04
NaOH	kg	1.645E-01	8.029E-04
H_2SO_4	kg	2.783E+00	1.359E-02
ZnO	kg	5.050E-01	2.465E-03
Calcium carbonate	kg	5.760E+00	2.812E-02
Charcoal	kg	5.350E+00	2.612E-02
Nickel	kg	1.160E-07	5.663E-10
Aluminium oxide	kg	1.160E-07	5.663E-10
Outputs			
Ash	kg	9.450E+00	4.613E-02
Waste water	m^3	2.909E-01	1.420E-03
Bed material	kg	9.500E+00	4.638E-02
Sorbalit	kg	1.070E+01	5.223E-02
Gypsum	kg	5.630E-01	2.748E-03
Nickel	kg	1.160E-07	5.663E-10
Aluminium oxide	kg	1.160E-07	5.663E-10

Air emissions

All the heat required is considered to be supplied by methane combustion, and is modelled according to the process 'natural gas, burned in boiler modulating >100kW', with 95% efficiency.

Global CO_2 emissions are corrected such that the overall carbon balance of the process is closed. Some carbon indeed ends up in the waste streams and effluents. This carbon is considered to be burned in one way or another, downstream of the gasification process (at the wastewater treatment or incineration plant, for example), and therefore ends up as CO_2. Total CO_2 emissions amount to 4.926 kg CO_2 per net Nm^3 of methane. They are considered to be emitted to air, high population density, just like the other emissions from the combustion process.

The emissions taking place in the combustion zone of the gasifier are indicated in (Felder 2004) and summarised in Tab. 18.26.

Tab. 18.26 Summary of emissions occurring in the gasification zone of the gasifier (Felder 2004).

Inputs/Outputs	Unit	Quantity per t_{DM} of wood	Quantity per Nm^3 of methane (net)
CO	kg	9.233E-01	4.507E-03
NO_x	kg	5.313E-01	2.594E-03
HC	kg	1.012E-01	4.941E-04
Dust	kg	1.455E-02	7.101E-05

The overall amount of waste heat (emitted to air, high population density) is determined according to the overall energy balance of the process. Total waste heat (incl. heat of methane combustion and waste heat from the gasification and methanation processes) is 36.6 MJ/Nm^3 of methane (net). Finally, it is considered that all electricity consumption is generating waste heat (to air, high population density) of the same amount of energy, according to the ecoinvent guidelines.

As mentioned previously, the possible contamination of waste wood (compared to forest or residual wood) has little effect on the performance of the gasification process (Reichenbach de Sousa 2001; De Sousa 2002). Considering that waste wood represents only 14% of the feed to the gasifier, the effect of possible wood contamination is not taken into account.

Infrastructure

The dataset ‘synthetic gas plant’ is used to describe the infrastructure of the production of methane from wood chips. Given the unit capacity of the plant (81’500 Nm^3 of syngas per day at 330 days/yr over 50 years), and the net yield of methane (0.270 Nm^3 of methane per Nm^3 of syngas), the infrastructure input is equal to 2.90E-9 unit/Nm^3 of methane.

The unit process raw data of ‘methanol, from synthetic gas, at plant’ is indicated in Tab. 18.27.

Tab. 18.27 Unit process data of the datasets ‘methane, 96 vol.-%, from synthetic gas, wood, at plant’.

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol.-%, from synthetic gas, wood, at plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				Nm3			
product	methane, 96 vol.-%, from synthetic gas, wood, at plant	CH	0	Nm3	1.00E+00			
technosphere	wood chips, mixed, u=120%, at forest	RER	0	m3	1.26E-2	1	1.33	(3,3,1,2,3,5); Yield based on PSI data (Ecogas project) plus calculations, distribution of wood qualities from IEA Task 33 CH report
	wood chips, mixed, from industry, u=40%, at plant	RER	0	m3	4.32E-3	1	1.33	
	waste wood chips, mixed, from industry, u=40%, at plant	CH	0	m3	2.75E-3	1	1.33	
	synthetic gas plant	CH	1	unit	2.90E-9	1	3.06	(2,4,1,1,1,5); Calculation
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	8.09E-4	1	1.24	(2,4,1,1,1,5); Based on PSI data (Ecogas project) plus calculations
	electricity, medium voltage, at grid	CH	0	kWh	9.30E-1	1	1.24	
	tap water, at user	CH	0	kg	1.39E+0	1	1.24	
	rape methyl ester, at esterification plant	CH	0	kg	1.93E-2	1	1.24	
	aluminium oxide, at plant	RER	0	kg	5.66E-10	1	1.24	
	zinc for coating, at regional storage	RER	0	kg	2.47E-3	1	1.24	
	nickel, 99.5%, at plant	GLO	0	kg	5.66E-10	1	1.24	
	charcoal, at plant	GLO	0	kg	2.61E-2	1	1.24	
	silica sand, at plant	DE	0	kg	4.64E-2	1	1.24	
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	0	kg	1.61E-3	1	1.33	(3,3,1,2,3,5); Calculation from a typical quality of untreated syngas from wood
	sulphuric acid, liquid, at plant	RER	0	kg	1.36E-2	1	1.33	
	transport, freight, rail	CH	0	tkm	7.11E-2	1	2.09	(4,5,na,na,na,na); Based on ecoinvent Guidelines, standard distances
	transport, lorry 28t	CH	0	tkm	5.47E-3	1	2.09	
	transport, lorry 16t	CH	0	tkm	3.54E-1	1	2.09	(4,5,na,na,na,na); Assumed transport distance of 50 km for a 50 MW plant
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.42E-3	1	1.24	(2,4,1,1,1,5); Based on PSI data (Ecogas project) plus calculations
	disposal, inert material, 0% water, to sanitary landfill	CH	0	kg	9.86E-2	1	1.24	
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.93E-2	1	1.24	
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.63E-2	1	1.24	
	disposal, wood ash mixture, pure, 0% water, to sanitary landfill	CH	0	kg	1.99E-2	1	1.24	
	electricity, low voltage, production UCTE, at grid	UCTE	0	kWh	8.17E-3	1	1.33	(3,3,1,2,3,5); Calculation, based on 'heat, natural gas, at boiler modulating' (according to heat supply from methane)
	industrial furnace, natural gas	RER	1	unit	2.06E-8	1	3.11	
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	4.93E+0	1	1.05	(1,1,1,1,1,1); Calculation, to close carbon balance
	Heat, waste	-	-	MJ	3.99E+1	1	1.14	(2,4,1,3,1,3); Based on ecoinvent guidelines, calculation from electricity consumption and energy balance
	Acetaldehyde	-	-	kg	7.36E-9	1	1.64	(3,3,1,2,3,5); Calculation, based on 'heat, natural gas, at boiler modulating' (according to heat supply from methane)
	Acetic acid	-	-	kg	1.10E-6	1	1.64	
	Benzene	-	-	kg	2.95E-6	1	1.64	
	Benzo(a)pyrene	-	-	kg	7.36E-11	1	3.11	
	Butane	-	-	kg	5.16E-6	1	1.64	
	Carbon monoxide, biogenic	-	-	kg	4.52E-3	1	5.12	
	Dinitrogen monoxide	-	-	kg	3.68E-6	1	1.64	
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	2.21E-16	1	3.11	
	Formaldehyde	-	-	kg	7.36E-7	1	1.64	
	Mercury	-	-	kg	2.21E-10	1	5.12	
	Methane, biogenic	-	-	kg	1.47E-5	1	1.64	
	Nitrogen oxides	-	-	kg	2.71E-3	1	1.64	
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	1.25E-6	1	3.11	
	Particulates, < 2.5 um	-	-	kg	7.17E-5	1	3.11	
	Pentane	-	-	kg	8.84E-6	1	1.64	
	Propane	-	-	kg	1.47E-6	1	1.64	
	Propionic acid	-	-	kg	1.47E-7	1	1.64	
	Sulfur dioxide	-	-	kg	4.05E-6	1	1.33	
	Toluene	-	-	kg	1.47E-6	1	1.64	
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	9.71E-5	1	1.58	(2,4,1,1,1,5); Based on PSI data from the Ecogas project
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	3.31E-4	1	1.58	
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	6.51E-5	1	1.58	

18.7 Data Quality Considerations

The simplified approach with a pedigree matrix has been used for calculating the standard deviation in all the datasets.

18.8 Cumulative Results and Interpretation

18.8.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in (Frischknecht et al. 2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

18.8.2 Selected LCI results

Tab. 18.28 shows selected LCI results and the cumulative energy demand for the various unit processes of this chapter.

Tab. 18.28 Selected LCI results and the cumulative energy demand.

		Name		waste wood chips, mixed, from industry, u=40%, at plant	synthetic gas, from wood, at fixed bed gasifier	synthetic gas, from wood, at fluidized bed gasifier	synthetic gas, production mix, at plant	methanol, from synthetic gas, at plant	methanol, from biomass, at regional storage	methane, 96 vol.-%, from synthetic gas, wood, at plant
		Location		CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	m3	Nm3	Nm3	Nm3	kg	kg	Nm3
		Infrastructure		0	0	0	0	0	0	0
LCIA results										
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	70.3	0.4	0.5	0.5	3.8	4.4	4.8
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	20.7	0.2	0.3	0.2	3.4	3.5	5.5
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.4	0.1	0.1	0.1	1.0	1.1	1.8
	cumulative energy demand	renewable energy resources, wind, solar,	MJ-Eq	0.5	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.4	9.0	8.7	8.9	63.2	63.3	66.2
LCI results										
resource	Land occupation	total	m2a	1.2E-1	3.2E-1	3.1E-1	3.2E-1	2.3E+0	2.3E+0	2.5E+0
air	Carbon dioxide, fossil	total	kg	4.7E+0	2.6E-2	3.4E-2	3.0E-2	2.6E-1	2.9E-1	3.5E-1
air	NMVOC	total	kg	5.9E-3	7.6E-5	7.9E-5	7.7E-5	1.1E-3	1.7E-3	1.3E-3
air	Nitrogen oxides	total	kg	2.7E-2	1.9E-4	2.1E-4	2.0E-4	1.7E-3	2.0E-3	4.0E-3
air	Sulphur dioxide	total	kg	1.1E-2	9.2E-5	1.1E-4	1.0E-4	8.6E-4	9.0E-4	7.5E-4
air	Particulates, < 2.5 um	total	kg	1.7E-3	1.5E-5	2.5E-5	2.0E-5	1.5E-4	1.7E-4	2.2E-4
water	BOD	total	kg	1.2E-2	1.1E-4	1.2E-4	1.1E-4	1.1E-3	1.2E-3	1.2E-3
soil	Cadmium	total	kg	2.5E-8	1.3E-10	1.4E-10	1.4E-10	1.3E-9	1.6E-9	-2.5E-8
Further LCI results										
air	Carbon dioxide, biogenic	total	kg	-3.4E+2	-5.7E-1	-5.9E-1	-5.8E-1	-1.4E+0	-1.4E+0	-1.9E+0
air	Carbon dioxide, land transformation	low population density	kg	2.6E-5	1.1E-7	1.3E-7	1.2E-7	9.2E-7	1.1E-6	1.5E-6
air	Methane, biogenic	total	kg	3.8E-5	1.5E-6	1.6E-6	1.5E-6	2.1E-5	2.1E-5	8.2E-4
air	Carbon monoxide, biogenic	total	kg	2.1E-4	1.0E-5	1.0E-5	1.0E-5	8.4E-5	8.6E-5	7.3E-3
	biogenic C-content in product	calculated	kg	93.161	0.156	0.162	0.159	0.376	0.376	0.522
	CO2, biogenic-content in product	calculated	kg	341.589	0.570	0.592	0.581	1.377	1.378	1.915
	C-content in product	according to product properties -->	kg	93.273	0.155	0.161	0.158	0.375	0.375	0.525

The main results of this chapter shall now be compared to the ones found in the literature.

In particular, the cumulative energy demand[47] and greenhouse gas (GHG) emissions of "methanol, from biomass (at regional storage)" are compared with literature data. The comparison is shown in Tab. 18.29.

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[47] In the literature, the cumulative energy demand (CED) is often expressed as the so-called "energy ratio", i.e. the ratio of the energy produced in the form of biofuel to the equivalent non renewable primary energy consumed (i.e. energy out/energy in). This energy ratio is therefore equal to the ratio of the higher heating value (HHV) to the non renewable CED.

Tab. 18.29 Comparison of cumulative (non renewable) energy demand and CO_2 emissions with literature data.

			ecoinvent datasets		Literature								
			methanol, from biomass, at regional storage	methanol, at regional storage	(EcoTraffic 2001)	(GRI 1994)	(ETSU 1997)	(Greet 1998)	(ANL 2001)	(Delucchi 1997)	(Greet 2000)	(Acurex 1996)	This study
			kg										
HHV	MJ		22.700	22.700									
CED	$MJ_{n.r.}$		**7.189**	**7.858**	21.3	18.8	16.2	14.4	13.3	12.5	11.8	10.2	7.2
Energy ratio	MJ_{out}/MJ_{in}		**3.158**	**2.889**	1.07	1.20	1.40	1.57	1.72	1.82	1.92	2.22	3.16
CO_2, fossil	kg		**0.255**	**0.291**					1.00				0.26
CO_2, biogenic	kg		-1.377	-1.378									
IPCC 2001, GWP 100a	kg $CO_{2\ eq.}$	total	**-1.111**	**-1.075**									
IPCC 2001, GWP 100a	kg $CO_{2\ eq.}$	fossil	**0.272**	**0.310**									

The cumulative energy demand (CED) is here limited to non renewable energy (i.e. fossil and nuclear). The "Energy ratio" is calculated as the HHV of methanol (22.7 MJ/kg) to the calculated CED (in MJ/kg). As far as literature data is concerned, it is often difficult to know whether GHG emissions only include CO_2 or all of GHG according to IPCC, and are therefore quoted as CO_2 emissions, arbitrarily.

The data presented in Tab. 18.29 is illustrated in Fig. 18.19 (CED).

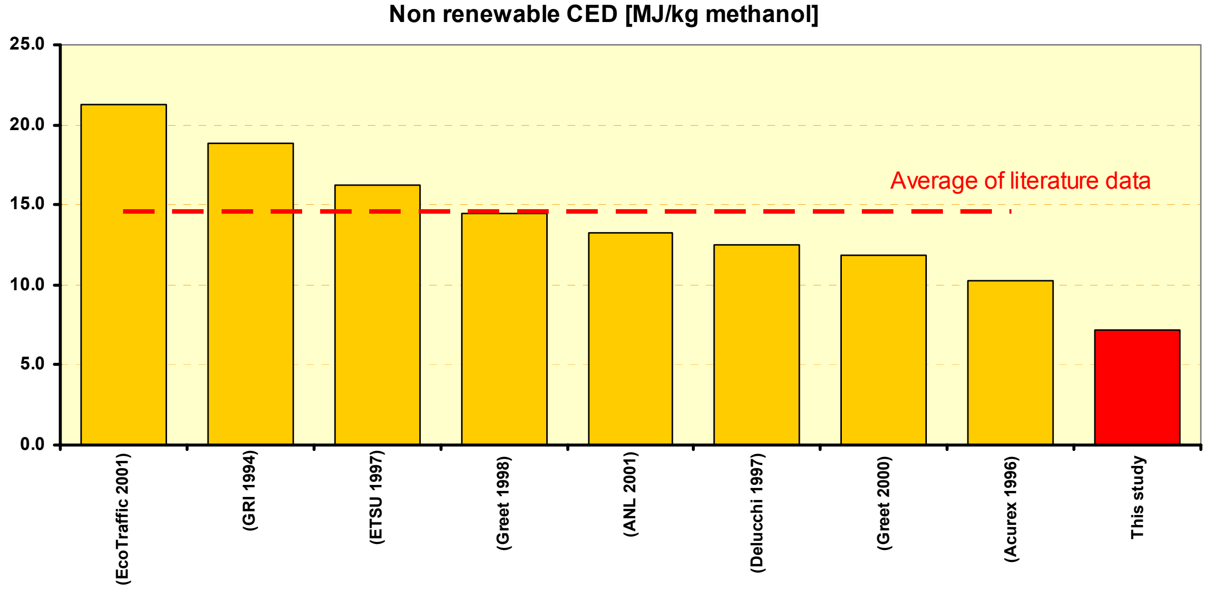

Fig. 18.19 Comparison of CED (non renewable) results with literature data.

The dotted line indicates the average of the literature data considered in the comparison. It shows that the cumulative energy demand obtained within this study is lower than the average and actually the minimum value compared to the quoted references. The number of literature sources, however, is not particularly large but is judged significant enough for comparison purposes. The biomethanol process suffers from the fact that the technology is not yet mature and is not studied as extensively as other biofuels (e.g. biodiesel, bioethanol) in terms of life cycle analyses.

It is very difficult to explain the differences as many factors can influence the results (e.g. inventory data, nature of biomass feedstock, technology, year of study, integration of the various processes in terms of energy use, plant size, methodology, structure and efficiency of energy systems, etc.). One of the facts explaining why the impact within this study should be lower than the average may be related to the choice of powering the processes with the syngas itself (instead of natural gas for example). On a general basis, the graph shows that the results obtained in the present study seem coherent with literature data.

As far as CO_2 is concerned, the data in Tab. 18.29 indicates that: as a fuel before use, methanol from biomass shows a negative net CO_2 balance (-1.111 kg CO_2/kg), i.e. the CO_2 credit from the initial biomass (-1.377 kg CO_2/kg) is larger than the fossil-based CO_2 emissions along the life cycle down to regional storage (+0.272 kg CO_2/kg).

In the case of CO_2, literature data proved to be particularly limited. Only one of the references considered addresses the issue of CO_2 balance (Tab. 18.29). The results obtained in this study seem to be significantly lower (compared with data found in the literature). This, again, could be explained by the fact that processes were chosen to be powered with wood chips (as opposed to natural gas for example). But again, there can be many other reasons why the results in the various literature sources should vary, and we will avoid here a tentative explanation as detailed hypotheses are often too limited in the literature.

As far as methane from syngas is concerned, hardly any LCA data is available in the literature, which made it difficult to compare the results of this study with literature data.

18.9 Conclusions

The production of methanol from biomass is based mainly on data relating to demonstration and/or pilot-scale installations, the technology being presently limited to such development stages. When biomass gasification and BTL processes develop, process parameters will require updating and benefit from more accurate data. Methanol synthesis from biomass can then be further detached from methanol synthesis from natural gas (as far as catalysts are concerned, etc.).

Also, because of the structure of the processes in the ecoinvent database, energy integration of the methanol synthesis and gasification processes could not be considered as effectively as possible. Methanol synthesis, indeed, develops quite significant amounts of energy which may be used in the gasification process, for drying purposes for exemple (biomass or syngas) and such aspects are here neglected.

Abbreviations

%mol.	percentage molar (equivalent to percentage volume when dealing with gases)
%vol.	percentage volume (equivalent to percentage molar when dealing with gases)
%wt.	percentage weight
Al	Aluminium
ATR	auto-thermal reforming
BCL	Battelle Columbus Laboratory
BFB gasifier	bubbling fluidized bed gasifier
BTL	biomass-to-liquid
BTX	benzene-toluene-xylene
CAS-No	chemical abstract service number (provides the chemical formula of a compound)
CFB gasifier	circulating fluidized bed gasifier
CGE	cold gas efficiency
CH_3OH	methanol
CH_4	methane
CHP	combined heat and power
C_nH_m	generic hydrocarbon molecule
Co	Cobalt
CO	carbon monoxide
CO_2	carbon dioxide
COS	carbonyl sulphide
CV	calorific value
ΔH	variation in enthalpy
DM	dry matter
DME	di-methyl ether
E/R	equivalence ratio
EF gasifier	entrained flow gasifier
FB gasifier	fluidized bed gasifier
Fe	Iron
FM	fresh matter
FR	Canton of Fribourg
FT	Fischer-Tropsch
H_2	hydrogen gas
H_2O	water
H_2S	hydrogen sulphide, also often referred to as sewer gas
H_2SO_4	sulphuric acid
HCl	hydrochloric acid
HCN	hydrogen cyanide
HHV	higher heating value

Ho	higher heating value
Hu	lower heating value
i-C_4	generic terminology for isobutene and isobutane
ICI	Imperial Chemical Industries PLC (methanol technology)
IGT	Institute of Gas Technology
IISc	Indian Institute of Science
kJ	kilojoule, 10^3 joules
kWh	kilowatt-hour
LCI	life cycle inventory
LCIA	life cycle inventory assessment
LHV	lower heating value
M100	pure methanol (terminology used in the sector of transportation)
M85	fuel blend consisting of a mixture of 85% methanol and 15% gasoline
MCE	mass conversion efficiency
MJ	megajoule, 10^6 joules
µm	micrometer
Mm^3	million cubic meters
MTBE	methyl tertiary butyl ether or methyl tert-butyl ether
MTCI	Manufacturing and Technology Conversion International, Inc. (gasifier manufacturer)
MW_e	megawatt of electrical energy
MW_{th}	megawatt of thermal energy
N_2	nitrogen gas
NaOH	sodium hydroxide, also often referred to as caustic soda or simply soda
NH_3	ammonia gas
Ni	Nickel
Nm^3	normal cubic meter
NO_x	nitrogen oxides
O_2	oxygen gas
PFB gasifier	pressurised fluidized bed gasifier
PJ	petajoule, 10^{15} joules
ppm	parts-per-million
S/B ratio	steam-to-biomass ratio
SMR	steam reforming
SO_x	sulphur oxides
Syngas	synthetic gas, also aften referred to as synthesis gas, producer gas or yet town gas
u	ratio of the weight of water to the weight of dry mass (applied to wood quality)
WGS	water gas shift
ZnO	zinc oxide

Glossary of terms

Cracking

In petroleum geology and chemistry, cracking is the process whereby complex organic molecules (e.g. kerogens or heavy hydrocarbons) are converted to simpler molecules (e.g. light hydrocarbons) by the breaking of carbon-carbon bonds in the precursors. The rate of cracking and the end products are strongly dependent on the temperature and presence of any catalysts.

Dimethyl ester (DME)

Dimethyl ether, also known as methoxymethane, methyl ether, wood ether, and DME, is a colorless gaseous ether with an ethereal smell. Dimethyl ether gas is water soluble. It has the formula CH3OCH3. Dimethyl ether is used as an aerosol spray propellant. Dimethyl ether is also a clean-burning alternative to liquified petroleum gas, liquified natural gas, diesel and gasoline. It can be made from natural gas, coal, or biomass.

Dolomite

Dolomite is the name of both a carbonate rock and a mineral (formula: $CaMg(CO_3)_2$) consisting of a calcium magnesium carbonate found in crystals. Dolomite rock (also dolostone) is composed predominantly of the mineral dolomite. Limestone which is partially replaced by dolomite is referred to as dolomitic limestone, or in old U. S. geologic literature as magnesian limestone.

Endothermic

In chemistry, an endothermic reaction is one in which the products have more energy than the reactants, and thus an net input of energy, usually in the form of heat, is required. Endothermic reactions are often described as reactions that "feel cold", and contrast with exothermic reactions, in which heat is released.

Exothermic

In chemistry, an exothermic reaction is one that releases heat. It is the opposite of an endothermic reaction.

Fischer-Tropsch

The Fischer-Tropsch process is a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms. Typical catalysts used are based on iron and cobalt. The principal purpose of this process is to produce a synthetic petroleum substitute.

Fixed bed

Fixed bed gasifiers have been the traditional technology for gasification, operated at temperatures around 1000°C. Depending on the direction of air flow, the gasifiers are classified as downdraft (also often referred to as co-current), updraft (also termed counter-current) or cross-flow.

Fluidised bed

A fluidised bed is formed when a quantity of a solid particulate substance (usually retained in a holding tank) is forced to behave as a fluid; usually by the forced introduction of pressurised gas through the particulate medium. This results in the medium then having many properties and characteristics of normal fluids; such as the ability to free-flow under gravity, or to pumped using fluid type technologies. It reduces the density of the medium; without affecting its elemental nature. Precautions must be taken against producing explosive vapours by combination with this process.

Methyl teritary- butyl ether (MTBE)

Methyl tertiary- butyl ether (MTBE) is a chemical compound that is manufactured by the chemical reaction of methanol and isobutylene. MTBE is produced in very large quantities and is almost exclusively used as a fuel component in motor gasoline. It is one of a group of chemicals commonly known as oxygenates because they raise the oxygen content of gasoline. At room temperature, MTBE is a volatile, flammable and colorless liquid that is relatively soluble in water. MTBE has a typical odor reminiscent of diethyl ether. MTBE is increasingly used in organic chemistry as a cheap solvent with properties comparable to diethyl ether but with a higher boiling point and lower solubility for water.

Oxidation

Oxidation describes the loss of an electron by a molecule, atom, or ion. Substances that have the ability to oxidise other substances are said to be oxidative and are known as oxidizing agents, oxidants or oxidizers. Put in another way, the oxidant removes electrons from the substance. Oxidants are usually chemical substances in high oxidation numbers (e.g. H_2O_2, MnO_4^-, CrO_3, OsO_4) or highly electronegative substances that can gain one or two extra electrons by oxidizing a substance (O_2, O_3, F_2, Cl_2, Br_2).

Steam reforming (SMR)

Steam reforming or steam methane reforming (SMR) is a method of producing hydrogen by water splitting. At high temperatures (700 – 1100 °C) and in the presence of a metal-based catalyst, steam reacts with methane to yield carbon monoxide and hydrogen.

Syngas

Syngas (from synthesis gas), also referred to as synthesis gas, synthetic gas or producer gas, is the name given to gasses of varying composition that are generated in coal or biomass gasification and some types of waste-to-energy facilities. The name comes from their use in creating synthetic petroleum for use as a fuel or lubricant via synthesis processes. Syngas consists primarily of carbon monoxide and hydrogen, and has less than half the energy density of natural gas. It also contains some sulfur compounds, a safety feature since this allows for its detection in the case of leakage.

Tar

Tar is a viscous black liquid derived from the destructive distillation of organic matter. Most tar is produced from coal as a byproduct of coke production, but it can also be produced from petroleum, peat or wood.

Water gas shift (WGS)

The water gas shift reaction is an organic reaction in which water and carbon monoxide react to carbon dioxide and hydrogen (water splitting). The water gas shift reaction is part of steam reforming of hydrocarbons and is involved in the chemistry of catalytic converters.

Appendices: EcoSpold Meta Information

Tab. A. 43 EcoSopld Meta Information of the unit process ‘waste wood chips, from industry, u=40%, at plant’.

Field name, IndexNumber	10010
Name	waste wood chips, mixed, from industry, u=40%, at plant
Location	CH
InfrastructureProcess	0
Unit	m3
Type	1
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This process includes transport of waste urban and demolition wood to the chopping facility (50 km), infrastructure, chopping of the wood into chips in the sawmill, consumption of water and disposal of effluents and wastes from sorting. Includes also the carbon dioxide credit. No specific treatment of the wood is considered. The gross calorific value of the biomass is not included as the product comes from waste.
Amount	1
LocalName	Holzschnitzel, Altholz, ab Aufbereitung
Synonyms	
GeneralComment	The distribution of wood qualities between hard and soft wood is 28% hard wood and 72% soft wood. The volume refers to the bulked volume. The bulk density of wood chips is 239 and 169 kg/m3 of dry mass, for hard and soft wood respectively (i.e.188.6 kg/m3 of dry mass overall). Lower heating value = 3640 MJ/m3. Waste wood does not go through a specific treatment process.
InfrastructureIncluded	1
Category	wood energy
SubCategory	fuels
LocalCategory	Holzenergie
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	2004
EndDate	2010
DataValidForEntirePeriod	1
OtherPeriodText	
Text	Data for Austria (process) and Switzerland (mix) used for central Europe
Text	Chopping of industrial residual wood in stationary electric chopper.
Percent	1
ProductionVolume	Production of waste urban and demolition wood in CH in 2003 is 0.2 million m3.
SamplingProcedure	Federal office of statistics (CH) and IEA task 33 country reports.
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	synthetic biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 44 EcoSopld Meta Information of the unit process 'synthetic gas plant'

Field name, IndexNumber	6399
Name	synthetic gas plant
Location	CH
InfrastructureProcess	1
Unit	unit
Type	1
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This infrastructure process includes land use, buildings and facilities (including dismantling) of a typical biomass gasifier. Process includes the dryer, the comminution equipment, the gasifier and the gas treatment and conditioning facility.
Amount	1
LocalName	Synthesegasanlage
Synonyms	syngas//synthesis gas
GeneralComment	Lifetime is assumed to be 50 years. Typical biomass gasifier of 5 MWth output (i.e. 7.2-7.6 MWth input) capacity, processing 32-35 t/day of wood (dry matter) to 80'000-83'000 Nm3/day of syngas (330 day/yr).
InfrastructureIncluded	1
Category	biomass
SubCategory	fuels
LocalCategory	Biomasse
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	2004
EndDate	2006
DataValidForEntirePeriod	1
OtherPeriodText	
Text	CH, not site-specific
Text	Swiss production of syngas is limited to pilot-scale fixed-bed gasifiers (Pyroforce, Xylowatt). Data is not specific to the technology (i.e. fixed bed or fluidised bed).
Percent	0
ProductionVolume	Installed CH syngas production capacity is 1-1.2 MWth out of 2 units.
SamplingProcedure	Dataser was adapted from ecoinvent process 'industrial furnace, coal, 1-10 MW'.
Extrapolations	none
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	synthetic biofuels
Validator	41
Details	automatic validation
OtherDetails	none

Tab. A. 45 EcoSopId Meta Information of the unit processes relating to synthetic gas production.

Field name, IndexNumber	6398	6397	6310
Name	synthetic gas, from wood, at fixed bed gasifier	synthetic gas, from wood, at fluidized bed gasifier	synthetic gas, production mix, at plant
Location	CH	CH	CH
InfrastructureProcess	0	0	0
Unit	Nm3	Nm3	Nm3
Type	1	1	1
Version	2.0	2.0	2.0
energyValues	0	0	0
LanguageCode	en	en	en
LocalLanguageCode	de	de	de
Person	65	65	65
QualityNetwork	1	1	1
DataSetRelatesToProduct	1	1	1
IncludedProcesses	This process refers to the conversion of wood chips into synthetic gas. It includes drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), fixed bed gasification of the wood chips and treatment of the resulting syngas to remove impurities and contaminants.	This process refers to the conversion of wood chips into synthetic gas. It includes drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), fluidized bed gasification of the wood chips and treatment of the resulting syngas to remove impurities and contaminants.	This process includes the production of synthetic gas from wood chips, 50% from Fixed bed gasification and 50% from Fluidized bed gasification.
Amount	1	1	1
LocalName	Synthesegas, aus Holz, ab Festbettvergasung	Synthesegas, aus Holz, ab Wirbelschichtvergasung	Synthesegas, Produktionsmix, ab Werk
Synonyms	syngas//synthesis gas	syngas//synthesis gas	syngas//synthesis gas
GeneralComment	Composition (% mol.) of the resulting gas is 28.4% H2, 40.6% CO, 23.6% CO2, 5.9% CH4 and 1.5% CnHm (mol.) on a nitrogen and water free basis. Nitrogen content is 47.6%. Density is 1.15 kg/Nm3. Lower heating value of the gas is 5.2 MJ/Nm3. Heat is supplied by syngas combustion. Inventory refers to the net production of 1 Nm3 syngas. Net gas yield is 1.466 Nm3/kg of wood (dry matter).	Composition (% mol.) of the resulting gas is 15.5% H2, 39.2% CO, 34.9% CO2, 8.7% CH4 and 1.7% CnHm on a nitrogen and water free basis. Nitrogen content is 50.4%. Density is 1.15 kg/Nm3. Lower heating value of the gas is 5.4 MJ/Nm3. Heat is supplied by syngas combustion. Inventory refers to the net production of 1 Nm3 syngas. Net gas yield is 1.545 Nm3/kg of wood (dry matter).	Wood gasification in CH is limited to the Fixed bed pilot plant experience (Pyroforce, Xylowatt). The hypothesis with respect to the syngas production mix is 50% Fixed bed and 50% Fluidized bed. Average composition (% mol.) of the resulting gas is 22.0% H2, 39.9% CO, 29.3% CO2, 7.3% CH4 and 1.6% CnHm on a nitrogen and water free basis. Nitrogen content is 49.0%. Density is 1.15 kg/Nm3. Average lower heating value of the mix is 5.3 MJ/Nm3.
InfrastructureIncluded	1	1	1
Category	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula			
StatisticalClassification			
CASNumber			
StartDate	1995	1995	1995
EndDate	2006	2006	2006
DataValidForEntirePeriod	1	1	1
OtherPeriodText	Data from 1995 to 2004, first large scale facilities in the near future	Data from 1995 to 2004, first large scale facilities in the near future	Data from 1995 to 2004, first large scale facilities in the near future
Text	Data from various literatures sources and gasification plants worldwide, and from one pilot plant in CH	Data from various literatures sources and gasification plants worldwide, and from one pilot plant in CH	Hypothesis on the possible mix of syngas in CH
Text	The technology corresponds to an average indirectly heated, atmospheric Fixed bed gasification, followed by a low temperature wet gas treatment. No energy integration with the subsequent processing of the gas is considered. The Fixed bed gasification plant is typically <2 MWth input capacity.	The technology corresponds to an average indirectly heated, atmospheric, circulating Fluidized bed gasification, followed by a low temperature wet gas treatment. No energy integration with the subsequent processing of the gas is considered. The Fluidized bed gasification plant is typically >10 MWth input capacity.	Technologies are Fixed bed and Fluidized bed gasification with equal shares (50%) with respect to the total production volume.
Percent	1	0	0
ProductionVolume	In 2004, CH syngas production is limited to 2 pilot-scale Fixed bed gasifiers.	In 2004, CH syngas production is limited to 2 pilot-scale Fixed bed gasifiers.	In 2004, CH syngas production is limited to 2 pilot-scale Fixed bed gasifiers.
SamplingProcedure	Cross-checking of various literature sources and pilot-to-demonstration plant operation data, adapted to Swiss context	Cross-checking of various literature sources and pilot-to-demonstration plant operation data, adapted to Swiss context	Hypothesis of a potential distribution of synthetic gas technologies and volumes in Switzerland.
Extrapolations	none	none	none
UncertaintyAdjustments	none	none	none
Person	67	67	67
DataPublishedIn	2	2	2
ReferenceToPublishedSource	40	40	40
Copyright	1	1	1
AccessRestrictedTo	0	0	0
CompanyCode			
CountryCode			
PageNumbers	synthetic biofuels	synthetic biofuels	synthetic biofuels
Validator	41	41	41
Details	automatic validation	automatic validation	automatic validation
OtherDetails	none	none	none

Tab. A. 46 EcoSopId Meta Information of the unit processes relating to methanol production and distribution.

Field name, IndexNumber	6388	6307
Name	methanol, from synthetic gas, at plant	methanol, from biomass, at regional storage
Location	CH	CH
InfrastructureProcess	0	0
Unit	kg	kg
Type	1	1
Version	2.0	2.0
energyValues	0	0
LanguageCode	en	en
LocalLanguageCode	de	de
Person	65	65
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	Raw materials including syngas, processing energy, estimate on catalyst use based on 'methanol from natural gas', emissions to air and water from process, plant infrastructure.	This process includes the transport of biomass-based methanol from the plant to the end user. Operation of storage tanks and fuel station. Emissions from evaporation and treatment of effluents.
Amount	1	1
LocalName	Methanol, aus Synthesegas, ab Werk	Methanol, aus Biomasse, ab Regionallager
Synonyms	methyl alcohol // methyl hydroxide // monohydroxymethane	methyl alcohol // methyl hydroxide // monohydroxymethane
GeneralComment	The process describes the production of methanol derived from syngas and refers to a full-methanol steam reforming process to obtain a 2.2:1 H2:CO ratio of the syngas for the sole production of methanol. No CO2 use, no Hydrogen production (assumed to be burned in the furnace).	Bottom-Up estimation based on plant data. Life time is 80 years. Product storage volume of storage tanks is 10'000 m3. The average storage time is 2 months. Thus total through flow in the life time is 4.8 mio. m3.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula	CH3OH	CH3OH
StatisticalClassification		
CASNumber	000067-56-1	000067-56-1
StartDate	1995	1995
EndDate	2006	2006
DataValidForEntirePeriod	1	1
OtherPeriodText	Data from 1995 to 2004, pilot scale, future technology	
Text	Data from few literature sources, largely based on methanol from natural gas.	Surveys mainly for DE and CH.
Text	Data refers to full-methanol steam reforming (as opposed to autothermal reforming) of syngas derived from biomass gasification.	Distribution of fuels
Percent	0	0
ProductionVolume	No commercial plant of methanol-from-biomass. Laboratory-to-pilot scale.	No commercial production of methanol-from-biomass. Laboratory-to-pilot scale.
SamplingProcedure	Production assessed with mixed data from literature and the ecoinvent 'methanol from natural gas' process. Data is considered relatively weak, as there is no commercial experience of methanol from bio-syngas. Representativity of the data seems difficult to assess.	Environmental reports and literature.
Extrapolations	none	none
UncertaintyAdjustments	none	none
Person	67	67
DataPublishedIn	2	2
ReferenceToPublishedSource	40	40
Copyright	1	1
AccessRestrictedTo	0	0
CompanyCode		
CountryCode		
PageNumbers	synthetic biofuels	synthetic biofuels
Validator	41	41
Details	automatic validation	automatic validation
OtherDetails	none	none

Tab. A. 47 EcoSopId Meta Information of dataset ‘methane, 96 vol.-%, from synthetic gas, wood, at plant’.

Field name, IndexNumber	6429
Name	methane, 96 vol.-%, from synthetic gas, wood, at plant
Location	CH
InfrastructureProcess	0
Unit	Nm3
Type	1
Version	2.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	65
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This process refers to the conversion of wood chips into synthetic methane (96% vol.) through gasification and subsequent methanation. It includes drying (down to 10-15% moisture) and further comminution of wood chips (down to a size of 30x30x30 mm), FICFB (Fast Internally Circulating Fluidised Bed of the BCL type) gasification of the wood chips, treatment and conditioning of the resulting syngas to remove impurities and contaminants, methanation of the the syngas to methane, and compression of methane to natural gas network pressure (30-70 bar).
Amount	1
LocalName	Methan, 96 Vol.-%, aus Synthesegas, Holz, ab Aufbereitung
Synonyms	
GeneralComment	Composition (% mol.) of the gas is 96% CH4 (min.). Density is 0.752 kg/Nm3. Lower heating value of the gas is 34.4 MJ/Nm3. Process heat is supplied by methane combustion. Inventory refers to the net production of 1 Nm3 syngas. Net methane yield is 0.205 Nm3/kg of wood (dry matter).
InfrastructureIncluded	1
Category	biomass
SubCategory	fuels
LocalCategory	Biomasse
LocalSubCategory	Brenn- und Treibstoffe
Formula	
StatisticalClassification	
CASNumber	
StartDate	2000
EndDate	2008
DataValidForEntirePeriod	1
OtherPeriodText	Data mainly from 2004, pilot scale, future technology
Text	Data from Paul Scherrer Institut (PSI, Switzerland) and the pilot gasification plant in Güssing (Austria)
Text	Gasification technology is FICFB (fast internally circulating fluidized bed of the BCL type). Technology for methanation is developed by PSI.
Percent	0
ProductionVolume	In 2004, CH syngas production is limited to 2 pilot-scale Fixed bed gasifiers.
SamplingProcedure	Data from one source, pilot-to-demonstration plant operation data
Extrapolations	Combustion of methane (for internal process energy use) is extrapolated from the emission profile of natural gas combustion.
UncertaintyAdjustments	none
Person	67
DataPublishedIn	2
ReferenceToPublishedSource	40
Copyright	1
AccessRestrictedTo	0
CompanyCode	
CountryCode	
PageNumbers	synthetic biofuels
Validator	41
Details	automatic validation
OtherDetails	none

References

Althaus et al. 2004	Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A. (2004) Life Cycle Inventories of Chemicals. Final report ecoinvent 2000 No. 8. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Babu 2002	Babu S.P. (2002) Revised draft biomass gasification for hydrogen production, Process description and research needs, IEA Thernal Gasification Task Leader, Gas Technology Institute, US.
Bandi et al. 2004	Bandi A. & Specht M. (2004) Gewinnung von methanol aus biomasse, Expertise im Auftrag der Union zur Förderung von Oel- und Proteinpflanzen (UFOP) e.V., Baden-Württemberg, Germany.
Bauer et al. 2003	Bauer C. (2003) Holzenergie In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Beenackers 1999	Beenackers A.A.C.M. (1999) Biomass gasification in moving beds: A review of European technologies, In: Renewable Energy 16, pp. 1180-1186, Pergamon.
BFS 2004	Swiss Federal Statistical Office (2004) La forêt et le bois en Suisse, Annuaire 2004, Office fédéral de la statistique et Office fédéral de l'environnement, des forêts et du paysage (OFEFP), Neuchâtel, CH.
Boerrigter et al.. 2002	Boerrigter H., den Uil H., Calis H-P. (2002) Green diesel from biomass via Fischer-Tropsch synthesis: New insights in gas cleaning and process design, Presented at: Pyrolysis and gasification of biomass and waste, Expert meeting, 1 October 2002, Strasbourg, France.
Boerrigter et al 2004	Boerrigter H. et al. (2004) Integrated biomass gasification and gas cleaning facility; ECN pilot-plant for biomass research, Presented at the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection in Rome, Italy.
Boerrigter et al. 2005	Boerrigter H. et al. (2005) "OLGA" tar removal technology, ECN Biomass, the Netherlands.
Bridgwater 2003	Bridgwater A.V. (2003) Renewable fuels and chemicals by thermal processing of biomass, In: Chemical Engineering Journal 91, pp. 87-102, Elsevier.
Bühler et al. 2004	Bühler R., Nussbaumer T. (2004) Country reports: Switzerland, IEA Bioenergy, Task 33: Gasification and EU Gasnet.
BUWAL 2003	BUWAL information (2003) Forests and wood in Switzerland, Swiss Agency for the Environment, Forests and Landscape (SAEFL/BUWAL), CH.
Calis et al. 2002	Calis H.P.A. et al. (2002) Preliminary techno-economic analysis of large-scale synthesis gas manufacturing from imported biomass, Shell Global Solutions, the Netherlands.
Carpentieri et al. 2005	Carpentieri M., Corti A., Lombardi L. (2005) Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal, In: Energy Conversion and Management 46, pp. 1790-1808, Elsevier.
Corti et al. 2004	Corti A., Lombardi L. (2004) Biomass integrated gasification combined cycle with reduced CO_2 emissions: Performance analysis and life cycle assessment, In: Energy 29, pp. 2109-2124, Elsevier.

De Sousa et al. 2000	De Sousa L.C., Stucki S., Marti T. (2000) Fluidized bed gasification of wood, urban waste wood and wood/plastic mixtures, Paul Scherrer Institute, Element Cycles Section, Villigen, CH.
Dong et al. 1997	Dong Y., Steinberg M. (1997) Hynol: an economical process for methanol production from biomass and natural gas with reduced CO_2 emission, In: Int. J. Hydrogen Energy, Vol. 22 No. 10/11, pp. 971-977, Pergamon.
Dowaki et al. 2005	Dowaki K., Mori S. (2005) Biomass energy used in a sawmill, In: Applied Energy 80, pp. 327-339, Elsevier.
ecoinvent Centre 2004	ecoinvent Centre (2004) ecoinvent data v1.1, Final reports ecoinvent 2000 No. 1-15. ISBN 3-905594-38-2. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Hamelinck et al. 2001	Hamelinck C.N. & Faaij A.P. (2001) Future prospects for production of methanol and hydrogen from biomass, University of Utrecht, Netherlands.
Hamelinck et al. 2003	Hamelinck C.N. et al. (2003) Production of FT transportation fuels from biomass: Technical options, process analysis and optimisation, and development potential, Energy research Centre of the Netherlands (ECN), the Netherlands.
Hamelinck et al. 2004	Hamelinck C.N. et al. (2004) Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential, In: Energy 29, pp. 1743-1771, Elsevier.
Hanaoka et al. 2005	Hanaoka T. et al. (2005) Effect of woody biomass components on air-steam gasification, In: Biomass and Bioenergy 28, pp. 69-76, Elsevier.
Faaij et al. 1997	Faaij A. et al. (1997) Gasification of biomass wastes and residues for electricity production, In: Biomass and Bioenergy, Vol. 12, No. 6, pp. 387-407, Pergamon.
Farla et al. 1995	Farla J.C.M., Hendriks C.A. & Blok K. (1995) Carbon dioxide recovery from industrial processes, In: Climatic Change, No. 29, pp. 439-461.
Felder 2004	Felder R. (2004). Ecological impact of the use of methane from wood gasification. Internal report within the Ecogas project. Paul Scherrer Institut (PSI), Villigen, Switzerland, 2004.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. & Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Fromentin et al. 2000	Fromentin A., Biollay F., Dauriat A. (2000) Etat des connaissances dans le domaine de la gazéification du bois, Rapport final, Laboratoire de Systèmes Energétiques (LASEN), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, CH.
Giordano 1998	Giordano P. (1998): Production d'éléctricité à partir du bois, Gazéificateur IISc-Dasag couplé à un moteur à gaz, Phase II, Programme de recherche sur la Biomasse, Rapport final, Office fédéral de l'énergie (OFEN), CH.
Jungbluth et al. 2002	Jungbluth N., Frischknecht R. and Faist M. (2002) Ökobilanz für die Stromerzeugung aus Holzbrennstoffen und Altholz. 81427. ESU-services for Bundesamt für Energie, Uster, retrieved from: www.energieforschung.ch.
Jungbluth 2004	Jungbluth N. (2004) Erdöl. In: Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.

Leung et al. 2004	Leung D.Y.C., Yin X.L., Wu C.Z. (2004) A review on the development and commercialization of biomass gasification technologies in China, In: Renewable and Sustainable Energy Reviews 8, pp. 565-580, Elsevier.
Li. et al. 2004	Li X.T. et al. (2004) Biomass gasification in a circulating fluidized bed, In: Biomass and Bioenergy 26, pp. 171-193, Elsevier.
Lv et al 2004	Lv P.M. et al. (2004) An experimental study on biomass air-steam gasification in a fluidized bed, In: Bioresource Technology 95, pp. 95-101, Elsevier.
Malcolm Pirnie, Inc. 1999	Malcolm Pirnie, Inc. (1999) Evaluation of the fate and transport of methanol in the environment, California, US.
Maniatis 2001	Maniatis K. (2001) Progress in biomass gasification: An Overview, Directorate General for Energy & Transport, European Comission, Brussels, Belgium.
McKendry 2002a	McKendry P. (2002a) Energy production from biomass (part 1): Overview of biomass, In: Bioresource Technology 83, pp. 37-46, Elsevier.
McKendry 2002b	McKendry P. (2002b) Energy production from biomass (part 2): Conversion technologies, In: Bioresource Technology 83, pp. 47-54, Elsevier.
McKendry 2002c	McKendry P. (2002c) Energy production from biomass (part 3): gasification technologies, In: Bioresource Technology 83, pp. 55-63, Elsevier.
Morita et al. 2004	Morita H. et al. (2004) Feasibility study of wood biomass gasification/molten carbonate fuel cell power system: Comparative characterization of fuel cell and gas turbine systems, In: Journal of Power Sources 138, pp. 31-40, Elsevier.
NETL 2004	NETL (2004) Gasification technologies, A program to deliver clean, secure and affordable Energy, National Energy Technology Laboratory (NETL), US.
Nussbaumer et al. 1998	Nussbaumer T. et al. (1998) Energy from wood, Technical and economic assessment of the technologies for the conversion of wood to heat, electricity and synthetic fuels, Final Report, Swiss Federal Office of Energy, CH.
OPET Finland 2002	OPET Finland, (2002) Review of Finnish biomass gasification technologies, Organisations for the Promotion of Energy Technologies (OPET) Report 4, Technical Research Centre of Finland (VTT), Finland.
Quaak et al. 2000	Quaak P., H. Knoef H. & Stassen H. (2000) Energy from Biomass: A Review of Combustion and Gasification Technologies, World Bank, Technical Paper No. 442, 77 pp. Available from the World Bank Publications.
Rafaschieri et al. 1999	Rafaschieri A., Rapaccini M., Manfrida G. (1999) Life cycle assessment of electricity production from poplar energy crops compared with conventional fossil fuels, In: Energy Conversion & Management 40, pp. 1477-1493, Pergamon.
Rao et al. 2004	Rao M.S et al. (2004) Stoichiometric, mass, energy and exergy balance analysis of countercurrent fixed bed gasification of post-consumer residues, In: Biomass and Bioenergy 27, pp. 155-171, Elsevier.
Reichenbach de Sousa 2001	Reichenbach de Sousa L.C. (2001) Gasification of wood, urban wastewood (Altholz) and other wastes in a fluidized bed reactor, ETH Dissertation No. 14207, EPFZ, Zürich, CH.
Rollins et al. 2002	Rollins M.L. et al. (2002) Economic evaluation of CO_2 sequestration technologies, Task 4: Biomass gasification-based processing, Final Technical Report.
Saynor et al. 2003	Saynor B., Bauen A., Leach M. (2003) The potential for renewable energy sources in aviation, Imperial College Centre for Energy Policy and Technology (ICCEPT), London, UK.
Schuster et al. 2001	Schuster G. et al. (2001) Biomass steam gasification-an extensive parametric modelling study, In: Bioresource Technology 77, pp. 71-79, Elsevier.

Spath et al. 2003	Spath P.L. & Dayton D.C. (2003) Preliminary screening: Technical and economic assessment of synthesis gas to fuels and chemicals with emphasis on the potential for biomass-derived syngas, Technical Report, National Renewable Energy Laboratory (NREL), Colorado, US.
TDA Research, Inc. 1993	TDA Research, Inc. (1993) Summary of the comparison of the production of methanol and ethanol from biomass study, Wheat Ridge, Colorado, US.
Tijmensen et al. 2002	Tijmensen M. et al. (2002) Exploration of the possibilities for production of Fischer-Tropsch liquids and power via biomass gasification, In: Biomass and Energy 23, pp. 129-152, Pergamon.
van Dijk et al. 1995	van Dijk K.M., van Dijk R., van Eekhout V.J.L., van Hulst H., Schipper W. & Stam J.H. (1995) Methanol from natural gas: Conceptual design & comparison of processes, Delft University of Technology, Delft, 286 pp.
van Ree et al. 1995	van Ree R., Oudhuis A., Faaij A. & Curvers A. (1995) Modelling of a biomass integrated gasifier/combined cycle (BIG/CC) system with the flowsheet simulation programme ASPEN+, Netherlands Energy Research Foundation ECN and Department of Science, Technology and Society/Utrecht University, Petten.
Werner et al. 2003	Werner F., Althaus H.-J., Künniger T., Richter K. and Jungbluth N. (2003) Life Cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent 2000 No. 9. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Williams et al. 1995	Williams R.H. et al. (1995) Methanol and hydrogen from biomass for transportation, In: Energy for Sustainable Development, Vol. 1, pp. 18-34.
Wu et al 2002	Wu C.Z. et al. (2002) An economic analysis of biomass gasification and power generation in China, In: Bioresource Technology 83, pp. 65-70, Elsevier.

19 Gaseous fuels at service station

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Summary

The data sets “natural gas, production mix, at service station” and “methane, 96 vol-%, from biogas, production mix, at service station” describe the energy and material requirements for the delivery of gas for power trains at service stations. Emissions due to gas losses at the service station are included. The production mix is based on the Swiss delivery situation where 2% of gas delivered from service stations are connected to the low pressure gas network (<0.1 bar), 6% to the medium pressure gas distribution network (0.1-1 bar), and 92% to high pressure network (1-5 bar). The emissions at the service stations differ for natural gas and methane from biogas due to the different compositions of the two gases. The data set “natural gas service station” describes the infrastructure for the service station. Data are based on the description of a small size service station. The data sets “methane, 96 vol-%, from biogas, high pressure, at consumer” and “methane, 96 vol-%, from biogas, low pressure, at consumer” describe the distribution of biogas in the natural gas distribution networks. They are based on the similar data sets of natural gas distribution (Faist Emmenegger et al. 2003).

19.1 Introduction

The use of natural gas and biogas as a fuel for cars is developing in Switzerland and Europa. Gas fuelled cars operate with conventional Otto engines.

This chapter describes the energy use, emissions and infrastructure requirements of service stations distributing natural gas and biogas in Switzerland as well as the distribution of biogas in the high and low pressure distribution networks. A data set describes the infrastructure of the service station. As the service stations are often still in the planning phase, there are only few data about service station operation.

The data sets are linked to the natural gas network (Faist Emmenegger et al. 2003).

19.2 Characterisation of gaseous fuels

The following table shows the composition and heating values of the investigated gaseous fuels.

Tab. 19.1 Characterisation of gaseous fuels at service station

	unit	biogas, raw Nm3	methane kg	methane, 96 Vol.-%, from biogas kg	methane, 96 Vol.-%, from biogas Nm3
Lower heating value (Hu)	MJ	24.0	38.0	45.8	34.5
Upper heating value (Ho)	MJ	26.6		50.7	38.1
Density 20°C	kg/m3	1.12	0.72	0.75	0.75
Oxygen	kg	0.46	0.00	0.06	0.04
Carbon, fossil	kg	0.00	0.00	0.00	0.00
Carbon, biogen	kg	0.53	0.75	0.70	0.53
Hydrogen	kg	0.12	0.25	0.23	0.17
Sulphur	mg/kg	268		6.65	6.65
CO2 Factor	kg/MJ	0.091	0.072	0.056	0.056
CO2 Factor	kg	1.95	2.75	2.56	1.93
waste heat	MJ/MJin	1.11	0.00	1.11	1.11
methane	kg	0.48	1.0	0.91	0.69
carbon dioxide	kg	0.63		0.052	0.039
nitrogen	kg	0.009		0.017	0.013
Hydrogen Sulfide	kg	7.58E-06		2.02E-05	1.52E-05
Oxygen	kg	0.004		0.019	0.014
Sum	kg	1.121		1.00	0.75
Formula			CH4	CH4 (96%)	CH4 (96%)
CAS			74-82-8	74-82-8	74-82-8
Source		*own calculations*			

19.3 Life Cycle Inventory of distribution of biogas

Biogas is distributed in the regular natural gas network when it reaches a quality similar to natural gas. The content of methane must be at least 96 vol-%. The distribution requirements (energy, leakages) are similar to those of natural gas. Only the emissions differ in their composition due to the different composition of biogas compared to natural gas. The data sets “methane, 96 vol-%, from biogas, high pressure, at consumer” and “methane, 96 vol-%, from biogas, low pressure, at consumer” are based on the similar data sets for natural gas (Faist Emmenegger et al. 2003) and use the same sources. The leakages are assumed to be the same amount as in the natural gas network (0.05% in the high pressure network, 0.72% in the low pressure network) but are calculated for the components with the composition of biogas (96 vol-% methane, 2 vol-% CO_2, 1 vol-% N_2, 1 vol-% O_2, see also Tab. 19.1). The energy requirements for the distribution (heating of gas) are 1.67 E-3 MJ/MJ in the high pressure network 2.0 E-4 MJ/MJ in the low pressure network.

Tab. 19.2: Unit process raw data and data quality indicators of "methane, 96 vol-%, from biogas, high pressure, at consumer".

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol-%, from biogas, high pressure, at consumer	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				MJ			
products	methane, 96 vol-%, from biogas, high pressure, at consumer	CH	0	MJ	1.00E+0			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	7.24E-5	1	1.09	(1,3,1,3,1,3); environmental report of an Italian company
	natural gas, burned in boiler atm. low-NOx condensing non-modulating <100kW	RER	0	MJ	1.67E-3	1	1.09	(1,3,1,3,1,3); environmental report of an Italian company
	methane, 96 vol-%, from biogas, at purification	CH	0	Nm3	2.90E-2	1	1.09	(2,1,1,3,1,3); leakage based on German data
	pipeline, natural gas, high pressure distribution network	CH	1	km	9.50E-10	1	3.01	(2,1,2,1,1,3); based on statistics
emission air, high population density	Heat, waste	-	-	MJ	2.61E-4	1	1.09	(1,3,1,3,1,3); environmental report of an Italian company
	Carbon dioxide, biogenic	-	-	kg	5.70E-7	1	1.12	(3,1,1,1,1,3); calculation based on gas composition and leakages
	Methane, biogenic	-	-	kg	9.95E-6	1	2.02	(3,1,1,1,1,3); calculation based on gas composition and leakages
	Hydrogen sulfide	-	-	kg	2.20E-10	1	1.52	(3,1,1,1,1,3); calculation based on gas composition and leakages

Tab. 19.3: Unit process raw data and data quality indicators of "methane, 96 vol-%, from biogas, low pressure, at consumer".

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol-%, from biogas, low pressure, at consumer	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				MJ			
products	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	1.00E+0			
technosphere	natural gas, burned in boiler atm. low-NOx condensing non-modulating <100kW	RER	0	MJ	2.00E-4	1	1.09	(1,3,1,3,1,3); gas statistics
	methane, 96 vol-%, from biogas, high pressure, at consumer	CH	0	MJ	1.007E+0	1	1.09	(1,3,1,3,1,3); based on heating value, incl. leakage
	pipeline, natural gas, low pressure distribution network	CH	1	km	2.81E-9	1	3.01	(2,1,2,1,1,3); based on statistics
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	8.20E-6	1	1.12	(3,1,1,1,1,3); calculation based on gas composition and leakages
	Methane, biogenic	-	-	kg	1.43E-4	1	2.02	(3,1,1,1,1,3); calculation based on gas composition and leakages
	Hydrogen sulfide	-	-	kg	3.17E-9	1	1.52	(3,1,1,1,1,3); calculation based on gas composition and leakages

Tab. 19.4: EcoSpold Meta Information of "methane, 96 vol-%, from biogas, high pressure, at consumer" and "methane, 96 vol-%, from biogas, low pressure, at consumer".

Name	methane, 96 vol-%, from biogas, low pressure, at consumer	methane, 96 vol-%, from biogas, high pressure, at consumer
Location	CH	CH
InfrastructureProcess	0	0
Unit	MJ	MJ
Type	1	1
Version	1.1	1.1
energyValues	1	1
LanguageCode	en	en
LocalLanguageCode	de	de
Person	296	296
QualityNetwork	1	1
DataSetRelatesToProduct	1	1
IncludedProcesses	This dataset describes the energy requirement and the emissions of the low pressure distribution network in Switzerland.	This dataset describes the energy requirement and the emissions of the high pressure distribution network in Switzerland.
Amount	1	1
LocalName	Methan, 96 Vol.-%, aus Biogas, Niederdruck, an Abnehmer	Methan, 96 Vol.-%, aus Biogas, Hochdruck, an Abnehmer
Synonyms		
GeneralComment	Total network losses are based on published data, repartition of losses on high and low pressure network on calculations with data for other countries.	Total network losses are based on published data, repartition of losses on high and low pressure network on calculations with data for other countries.
InfrastructureIncluded	1	1
Category	biomass	biomass
SubCategory	fuels	fuels
LocalCategory	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula		
StatisticalClassification		
CASNumber		
StartDate	2000-01	2000-01
EndDate	2000-12	2000-12
DataValidForEntirePeriod	1	1
OtherPeriodText		
Text	Energy requirements is based on environmental report of Italian company. Total leakages are specific for CH, HD-leakages are calculated out of the total with German data.	Energy requirements is based on environmental report of Italian company. Total leakages are specific for CH, HD-leakages are calculated out of the total with German data.
Text	The quantity of gas delivered in the low pressure network is estimated. Households and half of commercial and of others are assumed to be connected to the low pressure network	The quantity of gas delivered in the high and medium pressure network is estimated. Industry, power plants and half of commercial and of others are assumed to be connected to the high and medium pressure network .
Percent	100	100
ProductionVolume	93 PJ natural gas at 39 MJ/m3 in low pressure network	20 PJ natural gas at 39 MJ/m3 in high and medium pressure network
SamplingProcedure	statistics	statistics

19.4 Life Cycle Inventory of infrastructure

Data of the infrastructure (Tab. 19.5) are based on values for a service station with a small area, which corresponds to average Swiss conditions[48]. Quantity of gas sold is a planning value. A life span of 50 years is assumed. The requirements in the construction phase are partly considered in the data set "building, hall". The total turnover of gas sold in Swiss service stations was 1.5*10^6 kg in 2003.

Tab. 19.5: Data of the infrastructure of a small natural gas service station

Item	Quantity	Unit	Remark
Weight of compressor Brugg	4.3	t	Mostly steel (compressor, steel bottles)
Container and auxiliary units Brugg	26	t	Reinforced concrete; 3 weight-% steel (assumption)
Turnover (planned)	310'250 235'790	m^3/year kg/year	
Area of service station	35.5	m^2	Assumption: 25% of total area
Circulation area	106.5	m^2	Assumption: 75% of total area
Total area	142	m^2	Personal communication

Tab. 19.6: Unit process raw data and data quality indicators for "natural gas service station".

	Name	Location	Infrastructu	Unit	natural gas service station	Uncertainty	StandardDeviation95	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	natural gas service station	CH	1	unit	1.00E+0			
technosphere	reinforcing steel, at plant	RER	0	kg	5.08E+3	1	1.24	(2,4,1,1,1,5); Expert data for one service station
	concrete, normal, at plant	CH	0	m3	1.15E+1	1	1.24	(2,4,1,1,1,5); Expert data for one service station
	building, hall	CH	1	m2	3.55E+1	1	3.32	(5,5,1,1,1,5); Estimation
	transport, lorry 28t	CH	0	tkm	7.58E+2	1	2.09	(4,5,na,na,na,na); standard distances
	transport, freight, rail	CH	0	tkm	3.05E+3	1	2.09	(4,5,na,na,na,na); standard distances
	disposal, building, reinforced concrete, to recycling	CH	0	kg	2.60E+4	1	1.62	(5,5,1,1,1,5); Estimation
emission resource, land	Occupation, industrial area, built up	-	-	m2a	1.50E+3	1	1.88	(5,5,1,1,1,5); Estimation
	Occupation, traffic area, road network	-	-	m2a	5.60E+3	1	1.58	(2,4,1,1,1,5); Expert data for one service station
	Transformation, from unknown	-	-	m2	1.42E+2	1	2.06	(2,4,1,1,1,5); Expert data for one service station
	Transformation, to industrial area, built up	-	-	m2	3.55E+1	1	2.32	(5,5,1,1,1,5); Estimation
	Transformation, to traffic area, road network	-	-	m2	1.07E+2	1	2.06	(2,4,1,1,1,5); Expert data for one service station

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[48] Personal communication, Mr. D. Gut, IBB, 22.01.2002

Tab. 19.7: Ecospold Meta Information for "natural gas service station".

Name	natural gas service station
Location	CH
InfrastructureProcess	1
Unit	unit
Type	1
Version	1.1
energyValues	1
LanguageCode	en
LocalLanguageCode	de
Person	296
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	This data set includes land use for a natural gas service station as well as steel and concrete requirements for compressor and container.
Amount	1
LocalName	Erdgastankstelle
GeneralComment	This data set includes land use for a natural gas service station as well as steel requirements for compressor and container. Data stems from a service station with 310'000 m3 gas (236'000 kg) sold per year (in 365 days). It is assumed that steel and concrete are recycled. A life span of 50 years is assumed.
InfrastructureIncluded	1
Category	natural gas
SubCategory	production
LocalCategory	Erdgas
LocalSubCategory	Bereitstellung
StartDate	2001
EndDate	2001
DataValidForEntirePeriod	1
OtherPeriodText	personal communication
Text	Data for Switzerland
Text	Service station with steel compressor.
Percent	0
ProductionVolume	310'000 m3/a resp. 236'000 kg/a
SamplingProcedure	data for one service station
Extrapolations	none
UncertaintyAdjustments	none

19.5 Life cycle inventories of natural gas and biogas at service station

Biogas is usually injected in the natural gas network once it has the required quality, which is at least 96 vol-% of methane. Therefore the data sets "natural gas, …,at service station" and "methane, 96 vol-%, from biogas, …,at service station" differ only in the single emissions due to leckage because of the slightly different composition of natural gas and biogas. It makes no difference in the operation of the service station if biogas or natural gas is refuelled, except for emissions.

19.5.1 System characterisation

A service station with gas (natural gas or biogas) consists normally of a compressor, a gas purification system, a temporary storage for the compressed gas and a pump for delivering the compressed gas. The compressor extracts gas from the local gas network and compresses it in several compression stages up to 300 bar. Because of security reasons the energy used for compressing in the service station is electricity. Electricity requirements depend heavily on the initial pressure of the gas from the network. Electricity use of the compressor increases with a lower initial pressure.

19.5.2 Characterisation of the service station

A service station for gas (natural gas or biogas) is connected to the natural gas network, mostly to the high pressure network (about 92% of gas delivered[49]). Natural gas in the high pressure network has a pressure of 1-5 bar. It has to be compressed to 250-300 bar in a compressor at the service station and is delivered with 200 bar in the vehicle's tank. About 6% of gas is delivered in service stations that are connected to the medium pressure gas distribution network (0.1-1 bar), the remaining 2% of gas is from service stations connected to the low pressure gas network (<0.1 bar), see Tab. 19.8[50].

Tab. 19.8 Share of gas delivered in service stationsin Switzerland.

	Share of gas delivered
Low pressure (< 0.1 bar)	2%
Medium pressure (0.1-1 bar)	6%
High pressure (1-5 bar)	92%

In the natural gas service station, the gas delivery is accounted for in the mass unit kg. Natural gas has a net calorific value of 47.9 MJ/kg (see also Faist Emmenegger et al. 2003), whereas processed biogas with 96 vol-% methane has a net calorific value of 45.8 MJ/kg (see Tab. 19.1).

19.5.3 Use of the service station

The gas service station network in Switzerland and Europa is continually growing. In March 2004 there were 39 gas fuelling stations in Switzerland. By 2006 about 100 gas service stations should be operated in Switzerland. The refuelling operation differs slightly from refuelling diesel or gasoline. Gas service stations are mostly installed in the urban agglomeration.

19.5.4 Energy requirements

Electricity use for compression at the service station depends on the intitial pressure of the gas. Electricity use of a service station by high, medium and low initial pressure is described in Tab. 19.9. The values are based on a model for calculating the energy requirements of gas compressing from gasmobil ag and were calculated with the following formula.

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[49] Personal communication, Mr. R. Tschopp, gasmobil ag, 27.09.2004

[50] Personal communication, Mr. R. Tschopp, gasmobil ag, 27.09.2004

$$\text{specific compressor work : wts} = \frac{\kappa}{\kappa - 1} \cdot R \cdot T_1 \left[\left(\frac{p2}{p1} \right)^{\left(\frac{\kappa-1}{\kappa} \right)} - 1 \right]$$

Κ [--]: 1.4

R [kJ/kg/K]: universal gas constant (0.287 kJ/kg/K)

T1 [K]: temperature (288.15 K)

p2 [bar]: end pressure (200 bar)

p1 [bar]: pressure input (0.01-5 bar)

wts [kJ/kg]: specific compressor work

Tab. 19.9 Electricity use of service stations with high, medium and low initial pressure. Values are calculated with a model from gasmobil ag.

Initial pressure	**Electricity use**
	kWh/kg
Low pressure (< 0.1 bar)	0.722
Medium pressure (0.1-1 bar)	0.361
High pressure (1-5 bar)	0.208
Average (weighted with the shares of Tab. 19.8)	0.227

19.5.5 Emissions of service stations

Emissions of service station are due to gas leckages during the filling process of the tank. They originate from gas left in the coupling piece to the tank of the vehicle. The content of the piece leaks to the ambient air at the end of the fuelling operation. This piece has a diameter of about 3 cm and a length of about 4 cm (SWS 2001). The volume of the leckage is therefore about 0.028 l, which corresponds to 0.0045 kg gas (at 200 bar pressure of tank). A vehicle refuels about 20-30 kg natural gas. The leckage by the refuelling procedure is therefore about 0.018%. During the yearly revisions of the service station, natural gas also leaks from the pipes. These leckages correspond to about 0.001% of the total gas sold (Erdgas Zürich 2001). Leckages are therefore estimated to be about 0.02% of the refuelled quantity.

Tab. 19.10: Leckages at the service station by fuelling with natural gas resp. biogas.

Emission	**Unit**	**natural gas, at service station**	**methane, 96 vol-%, from biogas, at service station**
Unit		kg	kg
Methane	kg	1.77E-4	1.82E-4
Carbon dioxide	kg	2.81E-6	1.04E-5
Ethane	kg	8.55E-6	
Propane	kg	3.26E-6	
Butane	kg	1.48E-6	
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	8.17E-7	
Hydrogen sulfide	kg		4.04E-9

19.5.6 Life cycle inventory of gas delivery at the service station

Tab. 19.11: Unit process raw data and data quality indicators of "natural gas, … , at service station".

	Name	Location	InfrastructureProcess	Unit	natural gas, from high pressure network (1-5 bar), at service station	natural gas, from medium pressure network (0.1-1 bar), at service station	natural gas, from low pressure network (<0.1 bar), at service station	natural gas, production mix, at service station	UncertaintyType	StandardDeviation95 %	GeneralComment
	Location				CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	natural gas, from high pressure network (1-5 bar), at service	CH	0	kg	1.00E+0	0	0	0			
	natural gas, from medium pressure network (0.1-1 bar), at s	CH	0	kg	0	1.00E+0	0	0			
	natural gas, from low pressure network (<0.1 bar), at service	CH	0	kg	0	0	1.00E+0	0			
	natural gas, production mix, at service station	CH	0	kg	0	0	0	1.00E+0			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	2.08E-1	3.61E-1	7.22E-1	2.27E-1	1	1.06	(1,2,1,1,1,2); Model from industry expert
	natural gas, high pressure, at consumer	CH	0	MJ	4.79E+1	4.79E+1		4.69E+1	1	1.06	(1,2,1,1,1,2); Estimation from industry expert
	natural gas, low pressure, at consumer	CH	0	MJ			4.79E+1	9.58E-1	1	1.06	(1,2,1,1,1,2); Estimation from industry expert
	natural gas service station	CH	1	unit	8.48E-8	8.48E-8	8.48E-8	8.48E-8	1	3.06	(2,4,1,1,1,5); Expert data for one service station
emission air, high population density	Heat, waste	-	-	MJ	7.49E-1	1.30E+0	2.60E+0	8.19E-1	1	1.06	(1,2,1,1,1,2); Average from literature
	Methane, fossil	-	-	kg	1.77E-4	1.77E-4	1.77E-4	1.77E-4	1	2.05	(2,3,1,1,1,5); Data from industry expert
	Carbon dioxide, fossil	-	-	kg	2.81E-6	2.81E-6	2.81E-6	2.81E-6	1	2.05	(2,3,1,1,1,5); Data from industry expert
	Ethane	-	-	kg	8.55E-6	8.55E-6	8.55E-6	8.55E-6	1	2.05	(2,3,1,1,1,5); Data from industry expert
	Propane	-	-	kg	3.26E-6	3.26E-6	3.26E-6	3.26E-6	1	2.05	(2,3,1,1,1,5); Data from industry expert
	Butane	-	-	kg	1.48E-6	1.48E-6	1.48E-6	1.48E-6	1	2.05	(2,3,1,1,1,5); Data from industry expert
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	8.17E-7	8.17E-7	8.17E-7	8.17E-7	1	2.05	(2,3,1,1,1,5); Data from industry expert

Tab. 19.12: Unit process raw data and data quality indicators of "biogas, … , at service station".

	Name	Location	InfrastructureProcess	Unit	methane, 96 vol-%, from biogas, production mix, at service station	methane, 96 vol-%, from biogas, from high pressure network, at service station	methane, 96 vol-%, from biogas, from medium pressure network, at service station	methane, 96 vol-%, from biogas, from low pressure network, at service station	UncertaintyType	StandardDeviation95 %	GeneralComment
	Location				CH	CH	CH	CH			
	InfrastructureProcess				0	0	0	0			
	Unit				kg	kg	kg	kg			
product	methane, 96 vol-%, from biogas, from high pressure networ	CH	0	kg	0	1.00E+0	0	0			
	methane, 96 vol-%, from biogas, from medium pressure net	CH	0	kg			1.00E+0				
	methane, 96 vol-%, from biogas, from low pressure network	CH	0	kg	0	0	0	1.00E+0			
	methane, 96 vol-%, from biogas, production mix, at service	CH	0	kg	1.00E+0	0	0	0			
technosphere	electricity, medium voltage, at grid	CH	0	kWh	2.27E-1	2.08E-1	3.61E-1	7.22E-1	1	1.06	(1,2,1,1,1,2); Model from industry expert
	methane, 96 vol-%, from biogas, high pressure, at consumer	CH	0	MJ	4.49E+1	4.58E+1	4.58E+1		1	1.06	(1,2,1,1,1,2); Estimation from industry expert
	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	9.17E-1			4.58E+1	1	1.06	(1,2,1,1,1,2); Estimation from industry expert
	natural gas service station	CH	1	unit	8.48E-8	8.48E-8	8.48E-8	8.48E-8	1	3.06	(2,4,1,1,1,5); Expert data for one service station
emission air, high population density	Heat, waste	-	-	MJ	8.19E-1	7.49E-1	1.30E+0	2.60E+0	1	1.06	(1,2,1,1,1,2); Average from literature
	Methane, biogenic	-	-	kg	1.81E-04	1.81E-04	1.81E-04	1.81E-04	1	2.05	(2,3,1,1,1,5); Emission rate from industry expert
	Carbon dioxide, biogenic	-	-	kg	1.04E-05	1.04E-05	1.04E-05	1.04E-05	1	2.05	(2,3,1,1,1,5); Emission rate from industry expert
	Hydrogen sulfide	-	-	kg	4.01E-09	4.01E-09	4.01E-09	4.01E-09	1	2.05	(2,3,1,1,1,5); Emission rate from industry expert

19.5.7 EcoSpold Meta Information

Tab. 19.13: EcoSpold Meta Information of “natural gas, … , at service station”.

Name	natural gas, from high pressure network (1-5 bar), at service station	natural gas, from medium pressure network (0.1-1 bar), at service station	natural gas, from low pressure network (<0.1 bar), at service station	natural gas, production mix, at service station
Location	CH	CH	CH	CH
InfrastructureProcess	0	0	0	0
Unit	kg	kg	kg	kg
Type	1	1	1	1
Version	1.1	1.1	1.1	1.1
energyValues	1	1	1	1
LanguageCode	en	en	en	en
LocalLanguageCode	de	de	de	de
Person	296	296	296	296
QualityNetwork	1	1	1	1
DataSetRelatesToProduct	1	1	1	1
IncludedProcesses	This data set includes electricity requirements of a natural gas service station as well as emissions from losses.	This data set includes electricity requirements of a natural gas service station as well as emissions from losses.	This data set includes electricity requirements of a natural gas service station as well as emissions from losses.	This data set includes electricity requirements of a natural gas service station as well as emissions from losses.
Amount	1	1	1	1
LocalName	Erdgas, vom Hochdrucknetz (1-5 bar), ab Tankstelle	Erdgas, vom Mitteldrucknetz (0.1-1 bar), ab Tankstelle	Erdgas, vom Niederdrucknetz (<0.1 bar), ab Tankstelle	Erdgas, Produktionsmix, ab Tankstelle
Synonyms				
GeneralComment	This data set includes electricity requirements of a service station as well as emissions from losses. The initial pressure of gas is from the high pressure network (1-5 bar). VOC emissions are calculated from gas losses and composition of Swiss natural gas.	This data set includes electricity requirements of a service station as well as emissions from losses. The initial pressure of gas is from the medium pressure network (0.1-1 bar). VOC emissions are calculated from gas losses and composition of Swiss natural gas.	This data set includes electricity requirements of a service station as well as emissions from losses. The initial pressure of gas is from the low pressure network (<0.1 bar). VOC emissions are calculated from gas losses and composition of Swiss natural gas.	This data set includes electricity requirements of a service station as well as emissions from losses. The data set represents the Swiss mix of services stations with high (92%), medium (6%) and low (2%) initial pressure. VOC emissions are calculated from gas losses and composition of Swiss natural gas.
InfrastructureIncluded	1	1	1	1
Category	natural gas	natural gas	natural gas	natural gas
SubCategory	fuels	fuels	fuels	fuels
LocalCategory	Erdgas	Erdgas	Erdgas	Erdgas
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula				
StatisticalClassification				
CASNumber				
StartDate	2001	2001	2001	2001
EndDate	2001	2001	2001	2001
DataValidForEntirePeriod	1	1	1	1
OtherPeriodText	personal communication	personal communication	personal communication	personal communication
Text	Data for Switzerland	Data for Switzerland	Data for Switzerland	Data for Switzerland
Text	Service station with high initial gas pressure (1-5 bar)	Service station with medium initial gas pressure (0.1-1 bar)	Service station with low initial gas pressure (<0.1 bar)	Service station with a mix of with high (92%), medium (6%) and low
Percent	0	0	0	0
ProductionVolume				
SamplingProcedure	personal communication	personal communication	personal communication	personal communication
Extrapolations	none	none	none	none
UncertaintyAdjustments	none	none	none	none

Tab. 19.14: EcoSpold Meta Information of “biogas, … , at service station”.

Name	methane, 96 vol-%, from biogas, from high pressure network, at service station	methane, 96 vol-%, from biogas, from medium pressure network, at service station	methane, 96 vol-%, from biogas, from low pressure network, at service station	methane, 96 vol-%, from biogas, production mix, at service station
Location	CH	CH	CH	CH
InfrastructureProcess	0	0	0	0
Unit	kg	kg	kg	kg
Type	1	1	1	1
Version	1.1	1.1	1.1	1.1
energyValues	1	1	1	1
LanguageCode	en	en	en	en
LocalLanguageCode	de	de	de	de
Person	296	296	296	296
QualityNetwork	1	1	1	1
DataSetRelatesToProduct	1	1	1	1
IncludedProcesses	This data set includes electricity requirements of a biogas service station as well as emissions from losses.	This data set includes electricity requirements of a biogas service station as well as emissions from losses.	This data set includes electricity requirements of a biogas service station as well as emissions from losses.	This data set includes electricity requirements of a biogas service station as well as emissions from losses.
Amount	1	1	1	1
LocalName	Methan, 96 Vol.-%, aus Biogas, vom Hochdrucknetz (1-5 bar), ab Tankstelle	Methan, 96 Vol.-%, aus Biogas, vom Mitteldrucknetz (0.1-1 bar), ab Tankstelle	Methan, 96 Vol.-%, aus Biogas, vom Niederdrucknetz (<0.1 bar), ab	Methan, 96 vol-%, aus Biogas, Produktionsmix, ab Tankstelle
Synonyms	Kompogas, Naturgas	Kompogas, Naturgas	Kompogas, Naturgas	Kompogas, Naturgas
GeneralComment	The initial pressure of gas is from the high pressure network (1-5 bar). Air emissions are calculated from gas losses and composition of biogas.	The initial pressure of gas is from the medium pressure network (0.1-1 bar). Air emissions are calculated from gas losses and composition of biogas.	The initial pressure of gas is from the low pressure network (<0.1 bar). Air emissions are calculated from gas losses and composition of biogas.	The data set represents the Swiss mix of service stations with high (92%), medium (6%) and low (2%) initial pressure. Air emissions are calculated from gas losses and composition of biogas.
InfrastructureIncluded	1	1	1	1
Category	biomass	biomass	biomass	biomass
SubCategory	fuels	fuels	fuels	fuels
LocalCategory	Biomasse	Biomasse	Biomasse	Biomasse
LocalSubCategory	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe	Brenn- und Treibstoffe
Formula				
StatisticalClassification				
CASNumber				
StartDate	2001	2001	2001	2001
EndDate	2001	2001	2001	2001
DataValidForEntirePeriod	1	1	1	1
OtherPeriodText	personal communication	personal communication	personal communication	personal communication
Text	Data for Switzerland	Data for Switzerland	Data for Switzerland	Data for Switzerland
Text	Service station with high initial gas pressure (1-5 bar)	Service station with medium initial gas pressure (0.1-1 bar)	Service station with low initial gas pressure (<0.1 bar)	Service station with a mix of high (92%), medium (6%) and low (2%) initial gas pressure
Percent	0	0	0	0
ProductionVolume				
SamplingProcedure	personal communication	personal communication	personal communication	personal communication
Extrapolations	none	none	none	none
UncertaintyAdjustments	none	none	none	none

19.6 Data Quality Considerations

Natural gas service stations were developped in the last years. Therefore data on infrastructure and emissions are actually mostly planning values and no operation data. For energy use for compression, data of several refuelling stations could be collected. These data can be considered as quite good. The data used here for infrastructure and emissions should in the future be verified with operation data that are collected during a longer period of time.

19.7 Cumulative Results and Interpretation

19.7.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

19.7.2 LCI results and cumulative energy demand

Tab. 19.15 shows selected LCI results and the cumulative energy demand for the data sets “natural gas, production mix, at service station” and “methane, 96 vol-%, from biogas, production mix, at service station” as well as for the data set “natural gas service station”. Cumulative energy demand for “methane, 96 vol-%, from biogas, production mix, at service station” is about 6 times lower as for “natural gas, production mix, at service station”. Land occupation and cadmium emissions in soil as well as BOD emissions in water is higher for “methane, 96 vol-%, from biogas, production mix, at service station” as for “natural gas, production mix, at service station”, whereas it is the contrary for fossil carbon dioxide as well as NMVOC and nitrogen oxides in air.

Tab. 19.15 Selected LCI results and the cumulative energy demand for the data sets "methane, 96 vol-%, from biogas, production mix, at service station", "natural gas service station" and "natural gas, production mix, at service station".

		Name		methane, 96 vol-%, from biogas, production mix, at service station	natural gas service station	natural gas, production mix, at service station
		Location		CH	CH	CH
		Unit	Unit	kg	unit	kg
		Infrastructure		0	1	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.92E+00	2.09E+05	5.69E+01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	5.45E+00	3.81E+04	1.46E+00
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.74E+00	1.34E+04	5.29E-01
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.18E-02	6.66E+02	1.04E-02
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	4.08E-02	2.77E+04	1.71E-02
LCI results						
resource	Land occupation	total	m2a	1.65E-02	1.28E+04	5.04E-03
air	Carbon dioxide, fossil	total	kg	1.54E-01	1.88E+04	3.82E-01
air	NMVOC	total	kg	1.29E-04	2.32E+01	1.30E-03
air	Nitrogen oxides	total	kg	5.51E-04	6.26E+01	1.21E-03
air	Sulphur dioxide	total	kg	1.52E-03	4.12E+01	1.35E-03
air	Particulates, < 2.5 um	total	kg	3.45E-05	9.94E+00	3.53E-05
water	BOD	total	kg	2.63E-04	8.91E+01	3.43E-04
soil	Cadmium	total	kg	8.50E-11	2.30E-05	3.53E-11
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	-2.64E+00	6.24E+02	-3.55E-05
air	Methane, biogenic	total	kg	3.08E-02	4.64E-02	2.11E-06
air	Carbon monoxide, biogenic	total	kg	7.76E-04	7.65E+00	2.36E-06

References

Erdgas Zürich 2001	Erdgas Zürich (2001) Hr. Weber, Erdgas Zürich AG, Zürich.
Faist Emmenegger et al. 2003	Faist Emmenegger M., Heck T. and Jungbluth N. (2003) Erdgas. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz* (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Frischknecht et al. 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
SWS 2001	SWS (2001) Hr. Häfeli, Städtische Werke Solothurn, Solothurn.

Part II

II.iv. Transport Services

Authors: see individual chapter

Citation:

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20 Road Transport Services based on Biofuels and Alternative Fuels

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Summary

The present study is an extension of the ecoinvent study on transport services. It provides background data of transport services for vehicles running on so-called alternative fuels (e.g., natural gas) or on biofuels (e.g., methane from biogas, ethanol or rape seed methyl ester). The data represent average transport conditions in Switzerland. In order to quantify environmental impacts of transport services and relate transport datasets to other product life cycles, the environmental impacts (e.g., emissions) are related to passenger kilometres [pkm]. Environmental impacts due to transportation of goods are related to the reference unit of one tonne kilometre [tkm]. A tonne kilometre is defined as the transport of one tonne of goods by a certain transport service over one kilometre. In addition to vehicle operation (in this context comprising vehicle travel and precombustion), infrastructure processes such as vehicle maintenance, manufacturing and disposal as well as transport infrastructure construction, operation and disposal are also taken into account.

20.1 Introduction

Nowadays, alternative fuels are being used worldwide in a variety of vehicle applications. Using these alternative fuels in vehicles can generally reduce harmful pollutants and exhaust emissions. In addition, many of these fuels can be domestically produced and derived from renewable sources. The goal of the present study is to assess and compare the advantages and disadvantages of different fuel categories for environmental purposes. Emissions of greenhouse gases and air pollutants from a passenger car and a 28-t lorry are examined. In the following, the reference basis is set to a unit of transportation, the so-called vehicle kilometre [vkm]. In the case of transportation of passengers, the environmental impact is expressed as passenger kilometres [pkm], in the case of transportation of goods, the performance is described for an average payload and related to one tonne kilometre [tkm]. A tonne kilometre is defined as the transport of one tonne of goods by a certain transport service over one kilometre. The data refer to average conditions in Switzerland (e.g., average transport conditions).

Emission factors and energy consumption depend on various factors as for example weight or engine power of the vehicle, the technical concept (legislation) and operating conditions. For the present, emissions of a vehicle typical for the Swiss situation in 2002-2004 are considered. Regulated pollutants and, where possible (depending on the availability of reliable data), unregulated pollutants were considered.

Emission factors used in the present study are based on several different measurement campaigns. When comparing emission factors, huge scatter is found for some of the pollutants. This scatter is partly due to differences in engine type and age, but may also result from differences in the applied measurement technique. Therefore, if possible, emission factors have to be selected from sources offering a wide spectrum of measurements. An aggregation of available data has been done by Keller et al. (2005) and in the following, we generally refer to these aggregated data.

In addition to vehicle operation (in the context of ecoinvent comprising vehicle travel and precombustion), additional infrastructure processes such as vehicle maintenance, manufacturing and disposal as well as transport infrastructure construction, operation and disposal are also taken into account.

20.2 Characterisation and Application of Transport Services - Biofuels and Alternative Fuels

Transport processes, either transportation of passengers or transportation of goods, occur between nearly any two process steps of a product system and often are of importance for a product life cycle. The biofuel transport datasets provided in this study are primarily designed to provide background data of straightforward application in a variety of life cycle studies. The supply of generic transport datasets helps to avoid additional uncertainties due to the incorrect selection and application of highly specific transport data in situations where no such detailed information is readily available or required. Seen in this light, the provided datasets allow for a screening of the importance of transport processes within a product life cycle. For LCA-studies focussing on the impact of transport or even focussing on the comparison of different transport systems, the presented generic datasets may have to be replaced with more specific data, e.g. data dealing with different traffic situations (urban / rural environment etc.).

20.3 System Characterisation

20.3.1 Scope of the Project

In the present study, life cycle inventories are modelled for road transportation of passengers and goods using vehicles powered by several alternative fuels, most of them so-called biofuels. In detail, these include

- Compressed natural gas
- Methane, 96 vol-%, from biogas
- Ethanol 5%: a blend of 5 vol-% ethanol (99.7% in H_2O) with 95 vol-% low-sulphur, unleaded petrol
- Pure Methanol
- Rape seed methyl ester 5%: a blend of 5 vol-% rape methyl ester with 95 vol-% ultra low-sulphur diesel
- Pure Rape seed methyl ester.

For the first five cases, emissions due to transportation of passengers, i.e. a passenger car, were analysed. In the case of rape seed methyl ester, emissions due to transportation of goods (28-t lorry) were modelled.

20.3.2 Functional Unit

Along the lines of Spielmann et al. (2004), the transport datasets are related to life cycles of other products and using the reference unit of [km] for the operation of a vehicle, one passenger kilometre [pkm] for transportation of passengers and one tonne kilometre [tkm] for the transportation of goods. A tonne kilometre is defined as the unit of measure of goods transport, which represents the transport of one tonne of goods by a certain means of transportation over one kilometre.

20.3.3 Architecture of Inventories

The transport services are further subdivided into vehicle operation and vehicle transport. The environmental impacts due to vehicle operation comprise vehicle travel and precombustion. The environmental impacts due to vehicle travel, on the other hand, are often referred to as exhaust emissions or tail pipe emissions plus non-exhaust emissions due to vehicle motion, e.g. tyre abrasion. The environmental interventions due to vehicle transport summarise the interventions due to vehicle operation, vehicle fleet and road infrastructure.

So-called demand factors (see Spielmann et al. 2004) are used to link the transport service components to the reference flow of one passenger kilometre [pkm] or one tonne kilometre [tkm]. In the present study, we focus on Swiss conditions, where possible and if not mentioned otherwise.

20.3.4 Data Requirements and Assumptions

Temporal Scope

Vehicle operation data generally refer to a reference situation within 2002 and 2004. For cases where such data was not available, older measurements were used and the present situation was estimated in relationship to the reference case.

Infrastructure data as well as the allocation of infrastructure processes to the actual transport performance was adopted from Spielmann et al. (2004). Due to a lack of recent data, these data partly represents a situation within the last decade.

Geographical Scope

The presented transport modules refer to Swiss conditions. This includes Swiss data as well as data measured within Europe for situations which are also applicable to Switzerland.

20.4 Life Cycle Inventories Vehicle Operation - Biofuels and Alternative Fuels

In the following sections, the environmental interventions due to vehicle operation are presented. Data sources and assumptions are reported. These data include precombusion emissions, exhaust emissions or tail pipe emissions as well as non-exhaust emissions due to vehicle motion, e.g. tyre abrasion.

20.4.1 Functional Unit

The transport datasets “operation of a vehicle” are related to life cycles of other products and using the reference unit of [km].

20.4.2 System Boundaries

We distinguish between vehicles for transportation of passengers and vehicles for transportation of goods. Tab. 20.1 presents the vehicle categories as selected to be representative for the selected fuels and for Swiss conditions within the given temporal scope.

Vehicle operation contains all processes directly connected with the operation of the vehicles, i.e., tail pipe (exhaust) emissions and emissions due to tyre abrasion. In the context of the ecoinvent database, environmental impacts due to precombustion processes are also included.

Tab. 20.1 Characterisation of vehicles

ecoinvent Unit Process	Vehicle Category	Vehicle Types Included	EU-emission standard
Operation, passenger car	Light duty vehicle	Passenger car	Euro-3
Operation, lorry 28 t	Heavy duty vehicle	Lorry and trailer, articulated lorry	Euro-3

20.4.3 Method

Precombustion emissions emitted during the production of alternative fuels and biofuels are investigated in other chapters of this report.

For tail pipe emissions of passenger cars, measurements made with the New European Driving Cycle (NEDC) have been applied. This test cycle is performed on a chassis dynamometer and consists of a cold start, an urban driving, and an extra-urban driving part. It is used for emission certification of light duty vehicles in Switzerland and in the European Community. Thus, emission factors of passenger cars refer to a legislative driving cycle. Where possible, the sample consists of emission factors of several Euro-3 vehicles representing Swiss (or European) average distributions in the context of vehicle size, age, and exhaust gas treatment. In the case of Methanol, a data set for Euro-2 vehicles was available (Keller et al. 1998). This data set was updated according to the relative changes for petrol Euro-2 / Euro-3 vehicles and verified based on Karlsson (1999), Olsson et al. (1999), Ohlström et al. (2001), and EPA (2002).

Exhaust emissions of heavy duty vehicles have been derived on the basis of measurements made with the European Transient Cycle (ETC). This cycle is used for emission certification of heavy duty vehicles and has been developed based on real road cycle measurements of heavy duty vehicles, representing urban, rural and motorway driving. The conversion from emissions in [kg/kWh] as resulting from the measurements into [kg/km] has been performed using respective figures from Keller et al. (2004) for Euro-3 28-t lorries with average load factor (50%). Therefore, in the case of 28-t lorries, real-world emissions are modelled.

Additionally to biofuel and alternative fuel concepts, emission and fuel consumption data is also provided for a petrol and a diesel passenger car, as well as for a diesel 28-t lorry. These values are derived applying the same method as for biofuel and alternative fuel concepts and are hence directly comparable. Note that they are not part of the ecoinvent data.

20.4.4 Fuel Consumption

The fuel consumptions were derived from carbon balance calculations, considering the carbon contents of measured tail pipe emissions of CO_2, CO and CH_4 as given in Tab. 20.3. Following the ecoinvent procedure, the carbon contents of NMVOC-emissions were neglected. Tab. 20.2 presents the fuel consumption of an average passenger car and a 28-t lorry with average load for each of the considered fuel types. The fuel types are described in Section 20.3.1.The underlying vehicle specifications can be found in Tab. 20.1. For comparison, the fuel consumptions of the respective vehicles (Euro-3) run with petrol or diesel are also given (Keller et al. 2004, Keller et al. 2006).

Note that the calculated fuel consumptions were not always in good correspondence with the according literature values. One possible reason for the differences is that the measurements were based on a fuel with slightly different carbon content than the fuel specified within this study (e.g., in the case of natural gas and biogas); another possible reason is the neglection of the carbon content of NMVOC in the carbon balance. Such a difference was, for example, observed for Ethanol 5%. The fuel consumption given in literature sources was 1% lower for Ethanol 5% than it was for pure petrol. Based on the carbon balance, a 1% higher fuel consumption resulted (for Ethanol 5%). However, the uncertainty of measurements is usually in the same order of magnitude. The important measures, i.e. the tail pipe emissions as for example CO_2-emissions, are based on measurements. Therefore, the differences between tail pipe emissions of different fuels are in good correspondence with literature values.

Tab. 20.2 Fuel consumption derived from CO_2-, CO- and CH_4-tail pipe emission measurements and fuel consumption according to literature.

Fuel	Vehicle Category	Fuel Consumption Derived		Fuel Consumption Literature
		[kg/km]	[MJ/km]	[kg/km]
Petrol, low sulphur	Passenger car	6.25E-02	2.66E+00	6.26E-02
Diesel, low sulphur	Passenger car	5.51E-02	2.36E+00	5.51E-02
Natural gas	Passenger car	6.41E-02	3.08E+00	6.70E-02
Methane, 96 vol-% from biogas	Passenger car	6.73E-02	3.08E+00	6.70E-02
Ethanol 5%	Passenger car	6.32E-02	2.64E+00	6.20E-02
Methanol	Passenger car	1.30E-01	2.59E+00	1.21E-01
Rape seed methyl ester 5%	Passenger car	5.55E-02	2.36E+00	5.51E-02
Diesel, low sulphur	Lorry, 28 t	2.39E-01	1.02E+01	2.39E-01
Rape seed methyl ester	Lorry, 28 t	2.67E-01	9.92E+00	2.75E-01

20.4.5 Tail Pipe Emissions

The emission factors refer to a Euro-3 vehicle, in the case of the lorry, average load is assumed (Tab. 20.3). The emission factors were derived on the basis of a literature research (CPCB 2003; EPA 2002; Hendriksen et al. 2003; Keller et al. 1998; Keller et al. 2005; Lance and Anderson 2003; Lehmann 2002; Munack et al. 2003; Ohlström et al. 2001; Scharmer et al. 2001; UFOP 2004; VCA 2004). For details see documentation in the xml-files.

Trace elements in diesel and gasoline fuels are a source of heavy metal emissions. Alternative fuels are assumed to be free of such trace elements. Fuels consisting of blends of biogene fuels and diesel or gasoline are assumed to produce heavy metal emissions corresponding to their part of fossil fuel. The respective data of heavy metal emissions are adopted from Spielmann et al. (2004) and adjusted to the respective fuel consumptions.

Along the lines of the ecoinvent database, the values listed here for NMVOC do not include the emissions of benzene, toluene and xylene. In the case of petrol, diesel, ethanol 5% and pure rape seed methyl ester, particulate emissions were only measured as the total mass of particles. For distinction between PM2.5, coarse particles (particulates > 2.5 µm and < 10 µm) and particulates > 10 µm within the particle emissions of the latter fuels, the size distribution from Spielmann et al. (2004) was applied.

Tab. 20.3 Tail pipe emission factors.

		Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Passenger Car	Lorry, 28 t	Lorry, 28 t
Pollutant, unspecified	Unit	Petrol, low sulphur	Diesel, low sulphur	Natural gas	Methane, 96 vol-% from biogas	Ethanol 5%	Methanol	Rape seed methyl ester 5%	Diesel, low sulphur	Rape seed methyl ester
Carbon monoxide, fossil	[kg/km]	9.84E-04	6.10E-04	4.46E-04	0.00E+00	8.75E-04	0.00E+00	6.09E-04	1.63E-03	0.00E+00
Carbon monoxide, biogenic	[kg/km]	0.00E+00	0.00E+00	0.00E+00	4.46E-04	2.95E-05	9.31E-04	2.86E-05	0.00E+00	8.99E-04
Carbon dioxide, fossil	[kg/km]	1.97E-01	1.73E-01	1.72E-01	0.00E+00	1.89E-01	0.00E+00	1.66E-01	7.54E-01	3.97E-02
Carbon dioxide, biogenic	[kg/km]	0.00E+00	0.00E+00	0.00E+00	1.72E-01	6.36E-03	1.77E-01	7.80E-03	0.00E+00	7.14E-01
Methane, fossil	[kg/km]	5.42E-06	3.28E-06	4.51E-05	0.00E+00	4.79E-06	0.00E+00	3.37E-06	9.82E-06	0.00E+00
Methane, biogenic	[kg/km]	0.00E+00	0.00E+00	0.00E+00	4.51E-05	1.61E-07	1.44E-06	1.58E-07	0.00E+00	3.82E-06
Nitrogen oxides	[kg/km]	5.13E-05	5.18E-04	2.06E-05	2.06E-05	5.84E-05	3.84E-05	5.05E-04	6.78E-03	6.99E-03
Particulates, > 2.5 um, and < 10um	[kg/km]	1.48E-07	2.54E-06	0.00E+00	0.00E+00	1.47E-07	0.00E+00	2.32E-06	1.40E-05	8.67E-06
Particulates, < 2.5 um	[kg/km]	1.78E-06	3.04E-05	6.67E-07	6.67E-07	1.76E-06	0.00E+00	2.81E-05	1.68E-04	1.04E-04
Particulates, > 10 um	[kg/km]	7.60E-08	1.30E-06	0.00E+00	0.00E+00	7.52E-08	0.00E+00	1.19E-06	7.20E-06	4.45E-06
Dinitrogen monoxide	[kg/km]	2.60E-06	5.58E-06	8.66E-07	8.66E-07	2.57E-06	2.60E-06	5.58E-06	7.04E-06	7.04E-06
Ammonia	[kg/km]	2.00E-05	1.00E-06	3.45E-05	3.45E-05	1.90E-05	1.85E-06	1.00E-06	5.00E-06	5.00E-06
Sulfur dioxide	[kg/km]	6.26E-06	5.51E-06	9.77E-07	8.95E-07	5.99E-06	0.00E+00	5.25E-06	2.39E-05	0.00E+00
NMVOC	[kg/km]	6.74E-05	1.30E-04	1.05E-05	1.05E-05	5.84E-05	5.18E-05	1.29E-04	3.88E-04	1.63E-04
Benzene	[kg/km]	6.86E-06	1.81E-06	7.62E-07	7.62E-07	1.88E-06	2.74E-06	1.80E-06	6.83E-06	1.16E-06
Toluene	[kg/km]	8.87E-06	4.38E-07	5.25E-06	5.25E-06	8.71E-06	5.56E-06	4.15E-07	1.31E-06	0.00E+00
Xylene	[kg/km]	7.39E-06	1.09E-06	5.39E-06	5.39E-06	9.31E-06	5.28E-07	1.04E-06	3.27E-06	0.00E+00
Zinc	[kg/km]	4.69E-08	4.13E-08	0.00E+00	0.00E+00	4.45E-08	0.00E+00	3.74E-08	1.79E-07	0.00E+00
Copper	[kg/km]	7.97E-08	7.01E-08	0.00E+00	0.00E+00	7.57E-08	0.00E+00	6.36E-08	3.04E-07	0.00E+00
Cadmium	[kg/km]	4.69E-10	4.13E-10	0.00E+00	0.00E+00	4.45E-10	0.00E+00	3.74E-10	1.79E-09	0.00E+00
Chromium	[kg/km]	2.34E-09	2.06E-09	0.00E+00	0.00E+00	2.23E-09	0.00E+00	1.87E-09	8.95E-09	0.00E+00
Chromium VI	[kg/km]	4.69E-12	4.13E-12	0.00E+00	0.00E+00	4.45E-12	0.00E+00	3.74E-12	1.79E-11	0.00E+00
Nickel	[kg/km]	3.28E-09	2.89E-09	0.00E+00	0.00E+00	3.12E-09	0.00E+00	2.62E-09	1.25E-08	0.00E+00
Lead	[kg/km]	9.38E-10	4.54E-12	0.00E+00	0.00E+00	8.91E-10	0.00E+00	4.12E-12	1.97E-11	0.00E+00
Heat, waste	[MJ/km]	2.82E+00	2.50E+00	3.39E+00	3.29E+00	2.81E+00	2.94E+00	2.49E+00	1.09E+01	1.08E+01

20.4.6 Non-Exhaust Emissions

Non-exhaust emissions are mainly produced from tyre abrasion, break wear and road abrasion. Spielmann et al. (2004) give an overview of the kind and amounts of the respective emissions. Since these emission factors do not depend on the type of consumed fuel, the values given in Spielmann et al. (2004) were adopted for the present study and applied for each transport system. Tab. 20.4 lists a summary of these non-exhaust emission factors.

Tab. 20.4 Non-exhaust emission factors due to tyre abrasion, break wear and road abrasion in [kg/km].

Pollutant, unspecified, in [kg/km]	Category	Passenger Car	Lorry, 28 t
Particulates, < 2.5 um	air	6.70E-06	3.00E-05
Particulates, > 2.5 um, and < 10um	air	1.34E-05	7.08E-05
Particulates, > 10 um	air	7.80E-05	4.24E-04
Zinc	air	5.85E-07	3.38E-06
Copper	air	1.09E-08	6.31E-08
Cadmium	air	7.29E-10	4.21E-09
Chromium	air	6.56E-09	3.79E-08
Nickel	air	5.83E-09	3.37E-08
Lead	air	3.65E-09	2.10E-08
Zinc, ion	water	2.32E-06	8.35E-06
Copper, ion	water	4.33E-08	1.56E-07
Cadmium, ion	water	2.89E-09	1.04E-08
Chromium, ion	water	2.60E-08	9.36E-08
Nickel, ion	water	2.31E-08	8.32E-08
Lead	water	1.44E-08	5.20E-08
Zinc	soil	2.32E-06	8.35E-06
Copper	soil	4.33E-08	1.56E-07
Cadmium	soil	2.89E-09	1.04E-08
Chromium	soil	2.60E-08	9.36E-08
Nickel	soil	2.31E-08	8.32E-08
Lead	soil	1.44E-08	5.20E-08

Additionally to the above emissions, environmental impact due to evaporation of fuels (soak, diurnal evaporation) is also considered. In the case of gaseous fuels, it is assumed that the fuel tank is leak-proof and no emissions due to evaporation occur. For diesel and rape seed methyl ester fuels, on the other hand, emissions due to evaporation are too small to be measured. Thus, environmental impact due to evaporation is only considered for petrol and ethanol 5% (Keller et al. 2004). However, there is not a lot of experimental data available with respect to evaporative emissions from ethanol blends and the test results reported in the literature show increased emissions, no changes, or even reduced evaporative emissions. We therefore assumed similar evaporative emissions for both petrol and ethanol 5% (cf. IDIADA 2003). Tab. 20.5 lists the respective emission factors.

Tab. 20.5 Non-exhaust emission factors due to evaporation in [kg/km].

		Passenger Car	Passenger Car
Pollutant, unspecified, in [kg/km]	Category	Petrol, low sulphur	Ethanol 5%
Benzene	air	4.23E-07	4.23E-07
Toluene	air	1.59E-06	1.59E-06
Xylene	air	5.29E-07	5.29E-07
NMVOC	air	5.29E-05	5.29E-05

20.4.7 Summary Operation – Biofuels and Alternative Fuels

Tab. 20.6 gives an overview of the environmental interventions due to vehicle operation using alternative fuels, summarising tail pipe emissions and non-exhaust emissions. The respective figures for the uncertainty information are listed in Tab. 20.8.

Tab. 20.6 Life cycle inventory input data of the operation of passenger cars and a 28-t lorry in Switzerland (emission factors).

	Name	Location	Category	Sub-Category	Unit	operation, passenger car, natural gas	operation, passenger car, methane, 96 vol-%, from biogas	operation, passenger car, ethanol 5%	operation, passenger car, methanol	operation, passenger car, rape seed methyl ester 5%	operation, lorry 28t, rape methyl ester 100%
	Location					CH	CH	CH	CH	CH	CH
	Unit					km	km	km	km	km	km
Products	operation, passenger car, natural gas	CH			km	1					
	operation, passenger car, methane, 96 vol-%, from biogas	CH			km		1				
	operation, passenger car, ethanol 5%	CH			km			1			
	operation, passenger car, methanol	CH			km				1		
	operation, passenger car, rape seed methyl ester 5%	CH			km					1	
	operation, lorry 28t, rape methyl ester 100%	CH			km						1
Technosphere	natural gas, production mix, at service station	CH			kg	6.41E-02					
	methane, 96 vol-%, from biogas, production mix, at service station	CH			kg		6.73E-02				
	ethanol, 99.7% in H2O, from biomass, at service station	CH			kg			3.35E-03			
	methanol, from biomass, at regional storage	CH			kg				1.30E-01		
	petrol, low-sulphur, at regional storage	CH			kg			5.99E-02			
	rape methyl ester, at regional storage	CH			kg					2.92E-03	2.67E-01
	diesel, low-sulphur, at regional storage	CH			kg					5.25E-02	
emissions to air	Carbon monoxide, fossil		air	unspecified	kg	4.47E-04	0.00E+00	8.75E-04	0.00E+00	6.09E-04	4.99E-05
	Carbon monoxide, biogenic					0.00E+00	4.47E-04	2.95E-05	9.31E-04	2.86E-05	8.99E-04
	Carbon dioxide, fossil		air	unspecified	kg	1.72E-01	0.00E+00	1.89E-01	0.00E+00	1.66E-01	3.97E-02
	Carbon dioxide, biogenic					0.00E+00	1.72E-01	6.36E-03	1.77E-01	7.80E-03	7.14E-01
	Methane, fossil		air	unspecified	kg	4.51E-05	0.00E+00	4.79E-06	0.00E+00	3.37E-06	2.12E-07
	Methane, biogenic					0.00E+00	4.51E-05	1.61E-07	1.44E-06	1.58E-07	3.82E-06
	Nitrogen oxides		air	unspecified	kg	2.06E-05	2.06E-05	5.84E-05	3.84E-05	5.05E-04	6.99E-03
	Dinitrogen monoxide		air	unspecified	kg	8.66E-07	8.66E-07	2.57E-06	2.60E-06	5.58E-06	7.04E-06
	Sulfur dioxide		air	unspecified	kg	9.77E-07	8.95E-07	5.99E-06	0.00E+00	5.25E-06	0.00E+00
	Benzene		air	unspecified	kg	7.62E-07	7.62E-07	2.30E-06	2.74E-06	1.80E-06	1.16E-06
	PAH, polycyclic aromatic hydrocarbons		air	unspecified	kg	1.07E-09	1.07E-09	3.18E-09	5.35E-10	2.02E-09	0.00E+00
	NMVOC, non-methane volatile organic compounds, unspecified origin		air	unspecified	kg	1.05E-05	1.05E-05	1.11E-04	5.18E-05	1.29E-04	1.63E-04
	Toluene		air	unspecified	kg	5.25E-06	5.25E-06	1.03E-05	5.56E-06	4.15E-07	0.00E+00
	Xylene		air	unspecified	kg	5.39E-06	5.39E-06	9.84E-06	5.28E-07	1.04E-06	0.00E+00
	Ammonia		air	unspecified	kg	3.45E-05	3.45E-05	1.90E-05	1.85E-06	1.00E-06	5.00E-06
	Particulates, < 2.5 um		air	unspecified	kg	7.37E-06	7.37E-06	8.46E-06	6.70E-06	3.48E-05	1.34E-04
	Particulates, > 2.5 um, and < 10um		air	unspecified	kg	1.34E-05	1.34E-05	1.35E-05	1.34E-05	1.57E-05	7.95E-05
	Particulates, > 10 um		air	unspecified	kg	7.80E-05	7.80E-05	7.81E-05	7.80E-05	7.92E-05	4.28E-04
	Selenium		air	unspecified	kg	0.00E+00	0.00E+00	4.45E-10	0.00E+00	3.74E-10	0.00E+00
	Mercury		air	unspecified	kg	0.00E+00	0.00E+00	3.12E-12	0.00E+00	7.49E-13	0.00E+00
	Zinc		air	unspecified	kg	5.85E-07	5.85E-07	6.30E-07	5.85E-07	6.22E-07	3.38E-06
	Copper		air	unspecified	kg	1.09E-08	1.09E-08	8.66E-08	1.09E-08	7.45E-08	6.31E-08
	Cadmium		air	unspecified	kg	7.29E-10	7.29E-10	1.17E-09	7.29E-10	1.10E-09	4.21E-09
	Chromium		air	unspecified	kg	6.56E-09	6.56E-09	8.79E-09	6.56E-09	8.43E-09	3.79E-08
	Chromium VI		air	unspecified	kg	0.00E+00	0.00E+00	4.45E-12	0.00E+00	3.74E-12	0.00E+00
	Nickel		air	unspecified	kg	5.83E-09	5.83E-09	8.95E-09	5.83E-09	8.45E-09	3.37E-08
	Lead		air	unspecified	kg	3.65E-09	3.65E-09	4.54E-09	3.65E-09	3.65E-09	2.10E-08
emissions to soil	Zinc		soil	unspecified	kg	2.32E-06	2.32E-06	2.32E-06	5.85E-07	2.32E-06	8.35E-06
	Copper		soil	unspecified	kg	4.33E-08	4.33E-08	4.33E-08	1.09E-08	4.33E-08	1.56E-07
	Cadmium		soil	unspecified	kg	2.89E-09	2.89E-09	2.89E-09	7.29E-10	2.89E-09	1.04E-08
	Chromium		soil	unspecified	kg	2.60E-08	2.60E-08	2.60E-08	6.56E-09	2.60E-08	9.36E-08
	Nickel		soil	unspecified	kg	2.31E-08	2.31E-08	2.31E-08	5.83E-09	2.31E-08	8.32E-08
	Lead		soil	unspecified	kg	1.44E-08	1.44E-08	1.44E-08	3.65E-09	1.44E-08	5.20E-08
emissions to water	Zinc, ion		water	unspecified	kg	2.32E-06	2.32E-06	2.32E-06	2.32E-06	2.32E-06	8.35E-06
	Copper, ion		water	unspecified	kg	4.33E-08	4.33E-08	4.33E-08	4.33E-08	4.33E-08	1.56E-07
	Cadmium, ion		water	unspecified	kg	2.89E-09	2.89E-09	2.89E-09	2.89E-09	2.89E-09	1.04E-08
	Chromium, ion		water	unspecified	kg	2.60E-08	2.60E-08	2.60E-08	2.60E-08	2.60E-08	9.36E-08
	Nickel, ion		water	unspecified	kg	2.31E-08	2.31E-08	2.31E-08	2.31E-08	2.31E-08	8.32E-08
	Lead		water	unspecified	kg	3.65E-09	3.65E-09	4.54E-09	3.65E-09	3.65E-09	2.10E-08
Heat waste	Heat, waste		air	unspecified	MJ	3.39E+00	3.29E+00	2.81E+00	2.94E+00	2.49E+00	1.08E+01

20.5 Life Cycle Inventories of Transportation - Biofuels and Alternative Fuels

20.5.1 Functional Unit

Along the lines of Spielmann et al. (2004), the transport datasets are related to life cycles of other products and using the reference unit of one passenger kilometre [pkm] for transportation of passengers and one tonne kilometre [tkm] for the transportation of goods. Tonne kilometre is defined as the unit of measure of goods transport, which represents the transport of one tonne of goods by a certain means of transportation over one kilometre.

20.5.2 Method

The environmental interventions due to vehicle transport are modelled by linking the environmental interventions due to vehicle operation with impacts due to vehicle manufacturing, vehicle maintenance, vehicle disposal, road construction, operation and maintenance of roads and road disposal. Again, an average passenger car and an average 28-t lorry, as typical for the situation in Switzerland in 2002-2004, have been modelled for each of the considered fuel types.

For consistency, the kilometric performance, the infrastructure data, and the demand factors for the transport components have been adopted from Spielmann et al. (2004), i.e. are derived from the ecoinvent database. It is assumed, that these factors do not depend on the type of fuel. This means that for passenger cars an average utilization of 1.59 passengers per car was assumed. In the case of the 28-t lorry, an average load of 5.82 t per vehicle was assumed.

20.5.3 Summary Transport –Biofuels and Alternative Fuels

The applied demand factors are summarised in Tab. 20.7. The respective uncertainy information is given in Tab. 20.9.

Tab. 20.7 Life cycle inventory input data of transport processes of passenger cars and a 28-t lorry in Switzerland.

	Name	Location	Infra-structure Process	Unit	transport, passenger car, natural gas	transport, passenger car, methane, 96 vol-%, from biogas	transport, passenger car, ethanol 5%	transport, passenger car, methanol	transport, passenger car, rape seed methyl ester 5%	transport, lorry 28t, rape methyl ester 100%
	Location				CH	CH	CH	CH	CH	CH
	Unit				pkm	pkm	pkm	pkm	pkm	tkm
Products	transport, passenger car, natural gas	CH	0	pkm	1					
	transport, passenger car, methane, 96 vol-%, from biogas	CH	0	pkm		1				
	transport, passenger car, ethanol 5%	CH	0	pkm			1			
	transport, passenger car, methanol	CH	0	pkm				1		
	transport, passenger car, rape seed methyl ether 5%	CH	0	pkm					1	
	transport, lorry 28t, rape methyl ester 100%	CH	0	tkm						1
transport components	operation, passenger car, natural gas	CH	0	km	6.29E-01					
	operation, passenger car, methane, 96 vol-%, from biogas	CH	0	km		6.29E-01				
	operation, passenger car, ethanol 5%	CH	0	km			6.29E-01			
	operation, passenger car, methanol	CH	0	km				6.29E-01		
	operation, passenger car, rape seed methyl ether 5%	CH	0	km					6.29E-01	
	operation, lorry 28t, rape methyl ester 100%	CH	0	km						1.72E-01
	passenger car		1	unit	4.19E-06	4.19E-06	4.19E-06	4.19E-06	4.19E-06	
	maintenance, passenger car		1	unit	4.19E-06	4.19E-06	4.19E-06	4.19E-06	4.19E-06	
	disposal, passenger car		1	unit	4.19E-06	4.19E-06	4.19E-06	4.19E-06	4.19E-06	
	lorry 28t		1	unit						3.18E-07
	maintenance, lorry 28t		1	unit						3.18E-07
	disposal, lorry 28t		1	unit						3.18E-07
	road		1	ma	4.36E-04	4.36E-04	4.36E-04	4.36E-04	4.36E-04	1.99E-03
	operation, maintenance, road		1	ma	7.93E-04	7.93E-04	7.93E-04	7.93E-04	7.93E-04	2.17E-04
	disposal, road		1	ma	4.36E-04	4.36E-04	4.36E-04	4.36E-04	4.36E-04	1.99E-03

20.6 Data Quality Considerations

The uncertainty of the inventory input data, was, where possible, adopted from the respective literature or derived from the uncertainty within the data sample. If there was no such information available, the simplified approach with a pedigree matrix has been used to calculate the standard deviation. Tab. 20.8 and Tab. 20.9 show the resulting measure of uncertainty.

Tab. 20.8 Uncertainty information on life cycle inventory input data of the operation of vehicles. * denotes uncertainty type normal distribution, the uncertainty type is lognormal otherwise.

		Standard Deviation 95%					
	Name	operation, passenger car, natural gas	operation, passenger car, methane, 96 vol-%, from biogas	operation, passenger car, ethanol 5%	operation, passenger car, methanol	operation, passenger car, rape seed methyl ester 5%	operation, lorry 28t, rape methyl ester 100%
	Location	CH	CH	CH	CH	CH	CH
Technosphere	natural gas, production mix, at service station	1.42					
	methane, 96 vol-%, from biogas, production mix, at service station		1.42				
	ethanol, 99.7% in H2O, from biomass, at service station			1.22			
	methanol, from biomass, at regional storage				1.65		
	petrol, low-sulphur, at regional storage			1.22			
	rape methyl ester, at regional storage					7.99E-04*	1.31
	diesel, low-sulphur, at regional storage					2.70E-03*	
emissions to air	Carbon monoxide, fossil	1.53		5.06		1.60E-05*	5.11
	Carbon monoxide, biogenic		1.53	5.06	5.39	4.74E-06*	5.11
	Carbon dioxide, fossil	1.42		1.22		2.70E-03*	1.31
	Carbon dioxide, biogenic		1.42	1.22	1.65	7.99E-04*	1.31
	Methane, fossil	1.51		1.56		2.00E-07*	1.63
	Methane, biogenic		1.51	1.56	1.90	5.92E-08*	1.63
	Nitrogen oxides	3.01	3.01	1.56	1.90	7.00E-06*	1.63
	Dinitrogen monoxide	1.51	1.51	1.56	1.90	1.57	1.63
	Sulfur dioxide	1.09	1.09	1.22		1.22	
	Benzene	1.51	1.51	1.56	1.90	1.57	1.63
	PAH, polycyclic aromatic hydrocarbons	3.01	3.01	3.05	3.34	3.05	
	NMVOC, non-methane volatile organic compounds, unspecified origin	1.51	1.51	1.56	1.90	1.57	1.63
	Toluene	1.52	1.52	1.56	1.90	1.57	
	Xylene	1.52	1.52	1.56	1.90	1.57	
	Ammonia	1.24	1.24	1.31	1.70	1.31	1.45
	Particulates, < 2.5 um	3.01	3.01	3.05	2.06	3.05	3.14
	Particulates, > 2.5 um, and < 10um	2.01	2.01	2.05	2.02	2.06	2.15
	Particulates, > 10 um	1.51	1.51	1.57	2.06	1.57	1.68
	Selenium			5.10		5.10	
	Mercury			5.10		5.10	
	Zinc	5.10	5.10	5.10	5.10	5.10	5.10
	Copper	5.10	5.10	5.10	5.10	5.10	5.10
	Cadmium	5.10	5.10	5.10	5.10	5.10	5.10
	Chromium	5.10	5.10	5.10	5.10	5.10	5.10
	Chromium VI			5.10		5.10	
	Nickel	5.10	5.10	5.10	5.10	5.10	5.10
	Lead	5.01	5.01	5.01	5.01	5.01	5.10
emissions to soil	Zinc	6.00	6.00	6.00	5.10	6.00	6.00
	Copper	6.00	6.00	6.00	5.10	6.00	6.00
	Cadmium	6.00	6.00	6.00	5.10	6.00	6.00
	Chromium	6.00	6.00	6.00	5.10	6.00	6.00
	Nickel	6.00	6.00	6.00	5.10	6.00	6.00
	Lead	6.00	6.00	6.00	5.01	6.00	6.00
emissions to water	Zinc, ion	6.00	6.00	6.00	6.00	6.00	6.00
	Copper, ion	6.00	6.00	6.00	6.00	6.00	6.00
	Cadmium, ion	6.00	6.00	6.00	6.00	6.00	6.00
	Chromium, ion	6.00	6.00	6.00	6.00	6.00	6.00
	Nickel, ion	6.00	6.00	6.00	6.00	6.00	6.00
	Lead	5.01	5.01	5.01	5.01	5.01	5.10
Heat waste	Heat, waste	1.11	1.11	1.11	1.11	1.11	1.11

Tab. 20.9 Uncertainty information on life cycle inventory input data of transport processes (uncertainty type and 95%-standard deviation).

		Uncertainty Type	Standard Deviation 95%					
	Name		transport, passenger car, natural gas	transport, passenger car, methane, 96 vol-%, from biogas	transport, passenger car, ethanol 5%	transport, passenger car, methanol	transport, passenger car, rape seed methyl ester 5%	transport, lorry 28t, rape methyl ester 100%
	Location		CH	CH	CH	CH	CH	CH
transport components	operation, passenger car, natural gas	1	1.14					
	operation, passenger car, methane, 96 vol-%, from biogas	1		1.14				
	operation, passenger car, ethanol 5%	1			1.14			
	operation, passenger car, methanol	1				1.14		
	operation, passenger car, rape seed methyl ether 5%	1					1.14	
	operation, lorry 28t, rape methyl ester 100%	1						1.10
	passenger car	1	1.11	1.11	1.11	1.11	1.11	
	maintenance, passenger car	1	1.11	1.11	1.11	1.11	1.11	
	disposal, passenger car	1	1.11	1.11	1.11	1.11	1.11	
	lorry 28t	1						1.11
	maintenance, lorry 28t	1						1.11
	disposal, lorry 28t	1						1.10
	road	1	1.10	1.10	1.10	1.10	1.10	1.10
	operation, maintenance, road	1	1.10	1.10	1.10	1.10	1.10	1.10
	disposal, road	1	1.10	1.10	1.10	1.10	1.10	1.10

Measurements of emission factors usually vary within a certain range of uncertainty and scatter. This scatter is due to several factors:

- Variance occurring for same test set-up, same fuel, same vehicle technology: Testing the same vehicle on the same test cycle may still result in a variance of emission factors of up to 20% while energy consumption (and thus CO_2-emissions) remain constant.
- Variance occurring for vehicles of same technology: Testing several comparable vehicles may result in a variance of emission factors of up to a factor 10, depending on vehicle type, manufacturer, and pollutant. For example, the scatter of NO_x-emissions is smaller than the scatter of CO-emissions.
- Variance due to differences in fuel composition: emission factors also depend on the quality and composition of fuels. Thus when comparing emission factors derived from different studies, variances in fuel composition may result in observed scatter.
- Variances due to different measurement set-ups: emission factors usually strongly vary for different test set-ups and for measurements conducted in different labs[51].

The data quality and uncertainty of infrastructure data is discussed in Spielmann et al. (2004).

20.7 Cumulative results and interpretation

20.7.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific in-

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[51] Calibration excercises between different labs help to reduce such variances.

puts from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

20.7.2 Operation

Tab. 20.10 shows selected LCI results and the cumulative energy demand for the operation of passenger cars and the 28t-lorry. It can be seen that the cumulative energy demand from both fossil and nuclear sources is lowest for cars operated with biogas, followed by cars operated by methanol. Including renewable energy resources, the total cumulative energy demand is still low for biogas but highest for methanol. The emission of fossil carbon dioxide is again smallest for the operation of a biogas-driven passenger car.

The LCI of fuel blends such as ethanol 5% or rape seed methyl ester 5% are – due to the rather low fraction of biofuel – comparable to the LCI of pure fossile fuels (i.e. petrol in the case of ethanol 5% and diesel in the case of rape seed methyl ester 5%, respectively).

Tab. 20.10 LCI results for transport processes (operation).

		Entry IndexNumber -->		6453	6360	6522	6362	6521	6523
		LCI_Sheet		_DATA_LCI_5.xls]Sheet 3	I_5.xls]Sheet 3	I_5.xls]Sheet 3	I_5.xls]Sheet 3	I_5.xls]Sheet 3	I_5.xls]Sheet 3
		Column		22	52	55	58	61	79
		Dataset-ID		6113	6114	6201	6115	6202	6205
		Name		operation, lorry 28t, rape methyl ester 100%	operation, passenger car, ethanol 5%	operation, passenger car, methane, 96 vol-%, from biogas	operation, passenger car, methanol	operation, passenger car, natural gas	operation, passenger car, rape seed methyl ester 5%
		Location		CH	CH	CH	CH	CH	CH
		Unit	Unit	km	km	km	km	km	km
		Infrastructure		0	0	0	0	0	0
LCIA results									
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	4.9	3.5	0.8	0.6	3.7	2.9
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.9	0.1	0.6	0.4	0.1	0.1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.3	0.0	0.2	0.1	0.0	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	13.2	0.2	0.0	8.2	0.0	0.1
LCI results									
resource	Land occupation	total	m2a	1.6E+0	7.4E-3	1.0E-3	3.0E-1	3.0E-4	1.9E-2
air	Carbon dioxide, fossil	total	kg	2.8E-1	2.3E-1	4.5E-2	3.8E-2	2.0E-1	2.0E-1
air	NMVOC	total	kg	5.0E-4	3.0E-4	4.1E-5	2.8E-4	1.1E-4	2.6E-4
air	Nitrogen oxides	total	kg	8.7E-3	2.4E-4	6.2E-5	3.0E-4	9.8E-5	6.5E-4
air	Sulphur dioxide	total	kg	4.6E-4	3.0E-4	8.7E-5	1.2E-4	8.9E-5	1.7E-4
air	Particulates, < 2.5 um	total	kg	2.8E-4	2.6E-5	1.1E-5	2.9E-5	9.7E-6	4.6E-5
water	BOD	total	kg	1.6E-3	7.4E-4	1.6E-5	1.6E-4	2.2E-5	5.6E-4
soil	Cadmium	total	kg	-4.7E-7	4.4E-9	2.9E-9	3.1E-9	2.9E-9	-2.3E-9
Further LCI results									
air	Carbon dioxide, biogenic	total	kg	-1.8E-3	-2.4E-3	-8.0E-3	-1.8E-3	-1.8E-6	-4.7E-5
air	Carbon dioxide, land transformation	low population density	kg	7.8E-6	6.2E-7	2.0E-7	1.5E-7	5.2E-7	5.2E-7
air	Methane, biogenic	total	kg	1.1E-6	1.4E-5	2.0E-3	2.7E-6	1.3E-7	7.9E-8
air	Carbon monoxide, biogenic	total	kg	9.2E-4	1.5E-3	4.5E-4	9.4E-4	1.5E-7	2.9E-5

20.7.3 Transport

Tab. 20.11 shows selected LCI results and the cumulative energy demand for demand for the transport processes of passenger cars and the 28t-lorry. The results are comparable with the results for the operation of the vehicles.

Tab. 20.11 LCI results for transport processes (transport).

		Entry IndexNumber -->		6364	6365	6526	6367	6525	6527
		LCI_Sheet		_DATA_LCI_5.xls]Sheet 3	l_5.xls]Sheet 3	l_5.xls]Sheet 3	l_5.xls]Sheet 3	l_5.xls]Sheet 3	l_5.xls]Sheet 3
		Column		109	133	136	139	142	160
		Dataset-ID		6116	6117	6203	6118	6204	6206
		Name		transport, lorry 28t, rape methyl ester 100%	transport, passenger car, ethanol 5%	transport, passenger car, methane, 96 vol-%, from biogas	transport, passenger car, methanol	transport, passenger car, natural gas	transport, passenger car, rape seed methyl ester 5%
		Location		CH	CH	CH	CH	CH	CH
		Unit	Unit	tkm	pkm	pkm	pkm	pkm	pkm
		Infrastructure		0	0	0	0	0	0
LCIA results									
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.7	2.7	1.0	0.9	2.8	2.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.3	0.4	0.7	0.6	0.4	0.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.1	0.2	0.2	0.1	0.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	2.3	0.2	0.0	5.2	0.0	0.1
LCI results									
resource	Land occupation	total	m2a	2.9E-1	1.2E-2	8.3E-3	1.9E-1	7.8E-3	1.9E-2
air	Carbon dioxide, fossil	total	kg	7.9E-2	1.7E-1	5.7E-2	5.2E-2	1.5E-1	1.5E-1
air	NMVOC	total	kg	2.2E-4	2.6E-4	9.4E-5	2.4E-4	1.3E-4	2.3E-4
air	Nitrogen oxides	total	kg	1.7E-3	2.4E-4	1.3E-4	2.8E-4	1.5E-4	4.9E-4
air	Sulphur dioxide	total	kg	1.5E-4	3.2E-4	1.8E-4	2.0E-4	1.8E-4	2.4E-4
air	Particulates, < 2.5 um	total	kg	6.7E-5	2.9E-5	2.0E-5	3.1E-5	1.9E-5	4.2E-5
water	BOD	total	kg	4.2E-4	5.5E-4	9.7E-5	1.8E-4	1.0E-4	4.4E-4
soil	Cadmium	total	kg	-8.0E-8	2.8E-9	1.8E-9	2.0E-9	1.8E-9	-1.4E-9
Further LCI results									
air	Carbon dioxide, biogenic	total	kg	-3.6E-4	-1.6E-3	-5.1E-3	-1.3E-3	-8.7E-5	-1.2E-4
air	Carbon dioxide, land transformation	low population density	kg	2.2E-6	1.1E-6	8.4E-7	8.0E-7	1.0E-6	1.0E-6
air	Methane, biogenic	total	kg	3.3E-7	9.1E-6	1.3E-3	2.0E-6	3.9E-7	3.6E-7
air	Carbon monoxide, biogenic	total	kg	1.7E-4	9.4E-4	3.0E-4	6.1E-4	1.5E-5	3.3E-5

Appendices: EcoSpold Meta Information

Tab. 20.12 Eco Spold Meta information of CNG (passenger car).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, passenger car, natural gas
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	natural gas, production mix, at service station supplies are included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included.
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Pkw, Erdgas
ReferenceFunction	491	Synonyms	
ReferenceFunction	492	GeneralComment	Average data for the operation of an Euro-3 Swiss passenger car.
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	2003
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions and kilometric performance of different passenger car categories in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	not known
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicati	751	Person	66
DataGeneratorAndPublicati	756	DataPublishedIn	2
DataGeneratorAndPublicati	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicati	758	Copyright	1
DataGeneratorAndPublicati	759	AccessRestrictedTo	0
DataGeneratorAndPublicati	760	CompanyCode	
DataGeneratorAndPublicati	761	CountryCode	
DataGeneratorAndPublicati	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Tab. 20.13 Eco Spold Meta information of methane, 96 vol-%, from biogas (passenger car).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, passenger car, methane, 96 vol-%, from biogas
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	methane, 96 vol-%, from biogas, production mix, at service station supplies are included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included.
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Pkw, Methan, 96 Vol.-%, aus Biogas
ReferenceFunction	491	Synonyms	
ReferenceFunction	492	GeneralComment	Average data for the operation of an Euro-3 Swiss passenger car.
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	2003
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions and kilometric performance of different passenger car categories in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	not known
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicati	751	Person	66
DataGeneratorAndPublicati	756	DataPublishedIn	2
DataGeneratorAndPublicati	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicati	758	Copyright	1
DataGeneratorAndPublicati	759	AccessRestrictedTo	0
DataGeneratorAndPublicati	760	CompanyCode	
DataGeneratorAndPublicati	761	CountryCode	
DataGeneratorAndPublicati	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Tab. 20.14 Eco Spold Meta information of ethanol, 5% (passenger car).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, passenger car, ethanol 5%
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	ethanol, 99.7% in H2O, from biomass, at service station, petrol, low-sulphur, at regional storage supplies are included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included.
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Pkw, bEnzin5
ReferenceFunction	491	Synonyms	
ReferenceFunction	492	GeneralComment	Average data for the operation of an Euro-3 Swiss passenger car.
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	2002
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions and kilometric performance of different passenger car categories in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	unknown
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicati	751	Person	66
DataGeneratorAndPublicati	756	DataPublishedIn	2
DataGeneratorAndPublicati	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicati	758	Copyright	1
DataGeneratorAndPublicati	759	AccessRestrictedTo	0
DataGeneratorAndPublicati	760	CompanyCode	
DataGeneratorAndPublicati	761	CountryCode	
DataGeneratorAndPublicati	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Tab. 20.15 Eco Spold Meta information of methanol (passenger car).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, passenger car, methanol
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	methanol, from biomass, at regional storage supplies are included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Pkw, Methanol
ReferenceFunction	491	Synonyms	MeOH
ReferenceFunction	492	GeneralComment	Average data for the operation of an Euro-3 Swiss passenger car.
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	2003
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions and kilometric performance of different passenger car categories in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	not known
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicati	751	Person	66
DataGeneratorAndPublicati	756	DataPublishedIn	2
DataGeneratorAndPublicati	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicati	758	Copyright	1
DataGeneratorAndPublicati	759	AccessRestrictedTo	0
DataGeneratorAndPublicati	760	CompanyCode	
DataGeneratorAndPublicati	761	CountryCode	
DataGeneratorAndPublicati	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Tab. 20.16 Eco Spold Meta information of rape seed methyl ester, 5% (passenger car).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, passenger car, rape seed methyl ester 5%
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	rape methyl ester, at regional storage, diesel, low-sulphur, at regional storage supplies are included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included.
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Pkw, Rapsölmethylester 5%
ReferenceFunction	491	Synonyms	RME
ReferenceFunction	492	GeneralComment	
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	2003
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions and kilometric performance of different passenger car categories in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	not known
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicati	751	Person	66
DataGeneratorAndPublicati	756	DataPublishedIn	2
DataGeneratorAndPublicati	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicati	758	Copyright	1
DataGeneratorAndPublicati	759	AccessRestrictedTo	0
DataGeneratorAndPublicati	760	CompanyCode	
DataGeneratorAndPublicati	761	CountryCode	
DataGeneratorAndPublicati	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Tab. 20.17 Eco Spold Meta information of rape seed methyl ester (lorry 28t).

Type	ID	Field name	
ReferenceFunction	401	Name	operation, lorry 28t, rape methyl ester 100%
Geography	662	Location	CH
ReferenceFunction	493	InfrastructureProcess	0
ReferenceFunction	403	Unit	km
DataSetInformation	201	Type	1
DataSetInformation	202	Version	1
DataSetInformation	203	energyValues	0
DataSetInformation	205	LanguageCode	en
DataSetInformation	206	LocalLanguageCode	de
DataEntryBy	302	Person	66
DataEntryBy	304	QualityNetwork	1
ReferenceFunction	400	DataSetRelatesToProduct	1
ReferenceFunction	402	IncludedProcesses	rape methyl ester, at regional storage supplies is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Heavy metal emissions to water and to soil are included. Tyre abrasion is included.
ReferenceFunction	404	Amount	1
ReferenceFunction	490	LocalName	Betrieb, Lkw 28t, Rapsölmethylester
ReferenceFunction	491	Synonyms	RME
ReferenceFunction	492	GeneralComment	Average data for the operation of heavy duty vehicles (20-28t) in Switzerland, with an average load of 50%.
ReferenceFunction	494	InfrastructureIncluded	1
ReferenceFunction	495	Category	transport systems
ReferenceFunction	496	SubCategory	road
ReferenceFunction	497	LocalCategory	Transportsysteme
ReferenceFunction	498	LocalSubCategory	Strasse
ReferenceFunction	499	Formula	
ReferenceFunction	501	StatisticalClassification	
ReferenceFunction	502	CASNumber	
TimePeriod	601	StartDate	1999
TimePeriod	602	EndDate	2005
TimePeriod	603	DataValidForEntirePeriod	1
TimePeriod	611	OtherPeriodText	
Geography	663	Text	Data refers to average transport conditions in Switzerland.
Technology	692	Text	Euro3
Representativeness	722	Percent	0
Representativeness	724	ProductionVolume	not known
Representativeness	725	SamplingProcedure	National statistics, data from technical institutions and literature data.
Representativeness	726	Extrapolations	none
Representativeness	727	UncertaintyAdjustments	none
DataGeneratorAndPublicatio	751	Person	66
DataGeneratorAndPublicatio	756	DataPublishedIn	2
DataGeneratorAndPublicatio	757	ReferenceToPublishedSource	40
DataGeneratorAndPublicatio	758	Copyright	1
DataGeneratorAndPublicatio	759	AccessRestrictedTo	0
DataGeneratorAndPublicatio	760	CompanyCode	
DataGeneratorAndPublicatio	761	CountryCode	
DataGeneratorAndPublicatio	762	PageNumbers	Road transport services
DataSetInformation	208	ImpactAssessmentResult	0

Abbreviations

ETC	European Transient Cycle
Euro-3	European emission standard
NEDC	New European Driving Cycle
pkm	passenger kilometre
tkm	tonne kilometre

References

EPA 2002 — EPA (2002) Clean Alternative Fuels, Methanol Facts Sheet, EPA420-F-00-040, retrieved from www.epa.gov.

Frischknecht et al. 2004 — Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004c) Implementation of Life Cycle Impact Assessment Methods. Final report ecoin-

	vent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Hendriksen et al. 2003	Hendriksen P., Vermeulen R.J., Rijkeboer R.C., Bremmers D., Smokers R.T.M. and Winkel R.G. (2003) Evaluation of the environmental impact of modern passenger cars on petrol, diesel, automotive LPG, CNG. TNO Report No. 03.OR.VM.055.1/PHE, Netherlands Organisation for Applied Scientific Research, Delft.
IDIADA 2003	IDIADA (2003) Comparison of Fuel Tank Evaporative Emissions from E0 and E5 petrol, IDIADA Automotive Technology, Report LM030411, L'Albornar.
Karlsson 1999	Karlsson H.L. (1999) Regulated and Unregulated Emissions from a Flexible-Fuel SAAB Passenger Car Driven with Seven Different Fuels. MTC 6907B.
Keller et al. 1998	Keller et al. (1998) Ökoprofile von Treibstoffen. BUWAL Umwelt-Materialien Nr. 104, Bern.
Keller et al. 2004	Keller M., de Haan P., Knörr W., Hausberger, S. and Steven, H. (2004) Handbook Emission Factors for Road Transport, Version 2.1, Umweltbundesamt Berlin, Swiss Agency for the Environment, Forests and Landscape, Umweltbundesamt Wien, INFRAS, Bern.
Keller et al. 2006	Keller, M. Kljun, N. and Wüthrich, Ph. (2006, in press) Luft- und Klimaprofile von Treibstoffen, Aktualisierung 2005, Umwelt-Materialen Nr. 194, Swiss Agency for the Environment, Forests and Landscape, INFRAS, Bern.
Lehmann 2002	Lehman U. (2002) Bio-Ethanol Projekt, Untersuchungsbericht Nr. 202672, EMPA, Eidgenössische Materialprüfungs- und Forschungsanstalt, Dübendorf.
Lance & Anderson 2003	Lance D. and Andersson J. (2003) DfT Biofuels Evaluation - Final Report of Test Programme to Evaluate Emissions Performance of Vegetable Oil Fuel on Two Light Duty Diesel Vehicles. Ricardo Consulting Engineers, West Sussex.
Munack et al. 2003	Munack A., Stein H., Bünger J., Schröder O. and Krahl J. (2003) Systematische Untersuchungen der Emissionen aus der motorischen Verbrennung von RME, MK1 und DK. FAL Bundesforschungsanstalt für Landwirtschaft, Braunschweig.
Ohlström et al. 2001	Ohlström M., Mäkinen T., Laurikko J. and Pipatti R. (2001) New concepts for biofuels in transportation, VTT research notes.
Olsson et al. 1999	Olsson A.R., Elam I.N. and Energi, A. (1999) Exchange program, alternative options for purchase of environmentally friendly vehicles in Stockholm, KFB, Stockholm.
Scharmer 2001	Scharmer K. (2001) Biodiesel, Energie- und Umweltbilanz Rapsölmethylester, UFOP Union zur Förderung von Oel- und Proteinpflanzen e.V., Bonn.
Spielmann et al. 2004	Spielmann M., Kägi T., Stadler P. and Tietje O. (2004) Life Cycle Inventories of Transport Services. Final report ecoinvent 2000 No. 14. UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
UFOP 2004	Union zur Förderung von Oel- und Proteinpflanzen (2004): http://www.ufop.de/900.htm
VCA 2004	Vehicle Certification Agency (2004): http://www.vcycarfueldata.org.uk.

21 Life Cycle Inventories for Swiss Passenger Cars

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Last Changes: 2006

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Summary

The present study is an extension of the ecoinvent study on transport services. It provides data for passenger car operation differentiated with respect to fuel type and Euro-emission standards (Euro3, Euro4, Euro5). In addition, a dataset for a passenger car powered by petrol containing ETBE (Ethyl-Tertiary-Butyl Ether) is generated. The data represent emissions and fuel consumption of newly registered cars in Switzerland in the time period 2005 up to 2010.

21.1 Introduction

The road transport sector constitutes one of the main concerns of policy makers and other social actors due to the increasing demand for its services, the overwhelming dependence on imported oil from politically volatile regions and the growing amount of emissions of CO_2 and air pollutants, among other factors. Reversing current unsustainable trends in the road transport sector is a considerable challenge that requires a broad portfolio of options, especially in the passenger car sector (WBCSD 2004). Addressing this challenge requires a thorough understanding of the impact of alternative policies and technology options that could be pursued. For example, the role of alternative fuels in road passenger vehicles is being intensely discussed today (see for example (Pehnt 2003)).

The ecoinvent database constitutes an important support tool for the identification of ecologically meaningful pathways and policies towards a more sustainable transportation system. Life Cycle Assessment (LCA) relying on the ecoinvent database provides support to decision makers in the government and industry as well as other stakeholders in the identification of promising solutions to environmental problems and in assessing the impact of measures such as new emission standards, fuel economy improvements, etc. Within the framework of ecoinvent 2000 project, road transport datasets have been generated to supply sets of highly aggregated environmental interventions due to road transport services to complete the assessment of energy and material life cycles (Spielmann et al. 2004).

For road passenger transport this resulted, for instance, in one average passenger car, which represents a mix with respect to fuel type, emission standard, driving conditions and vehicle size. Therefore, it is important to improve the modelling of road transport options in the context of the ecoinvent database, such that ecoinvent datasets can adequately support the analysis of sustainable road transport options and consolidate its position as a recognized source of consistent Life Cycle Inventories (LCI) in the road transport sector in the Swiss context. Specific attention needs to be given to the modelling of passenger cars, a key issue of concern when it comes to the sustainability of mobility services.

In recent years, exhaust emissions from road vehicles have played a prominent role in Swiss environmental policies. For instance, limits on exhaust gases of passenger cars became effective in the years 1987, 1991, 1994, 1996, 2001 and 2006, respectively (Keller & Zbinden 2004; Keller et al. 2004). Furthermore, similar to the commitment of the European Automobile Manufacturers Association (ACEA) to ensure the reduction of CO_2-emissions of new cars (ACEA 2004), there is a target agreement between the Swiss association of car importers (auto-schweiz) and the Federal Department of the

Environment, Transport, Energy and Communications that calls for a reduction in the specific fuel consumption of newly registered cars from 8.4 litres per 100 km in the year 2000 to 6.4 litres in 2008 (auto-schweiz 2004).

In order to address the ongoing environmental improvements – with respect to exhaust emissions – of conventional passenger cars, LCI-datasets representing Swiss average new registered diesel and petrol car for selected years and Euro-Standards (2005/Euro3, 2006/Euro4 and 2010/Euro5) are generated. In addition, two dataset for passenger cars powered by petrol blended with 4 Vol.% and 15 Vol.% ETBE ((Ethyl-Tertiary-Butyl Ether) are generated.

The transport services are further subdivided into vehicle operation and the vehicle transport. The environmental impacts due to vehicle operation comprise vehicle travel and pre-combustion. The environmental impacts due to vehicle travel, on the other hand, are often referred to as exhaust emissions or tail pipe emissions plus non-exhaust emissions due to vehicle motion, e.g. tyre abrasion. The environmental interventions due to vehicle transport summarise the interventions due to vehicle operation, vehicle fleet and road infrastructure.

So-called demand factors (see Spielmann (2005)) are used to link the transport service components to the functional unit of one passenger kilometre [pkm].

21.2 Characterisation of Passenger Car Transport Services

In 2004, the Swiss passenger car fleet comprised 3’629 Mio vehicles. Newly registered cars in Switzerland are almost exclusively diesel and petrol vehicles. Alternative propulsion systems and fuels are currently negligible. For instance, in the first half of 2003, 131 compressed natural gas-vehicles have been newly registered (Carle 2005), corresponding to a share of less than 0.5% on the total number of new registrations in the same period.

In recent years there has been a considerable increase of diesel vehicles among the newly registered passenger cars from about 5% in 1997 up to 25% in 2004 (see Fig. 21-1). However, the share of diesel cars is still significantly below the average of diesel vehicles in Europe (almost 45%). For the year 2010, a further increase in the proportion of new vehicles up to 30% for the year 2010 is expected (Keller & Zbinden 2004).

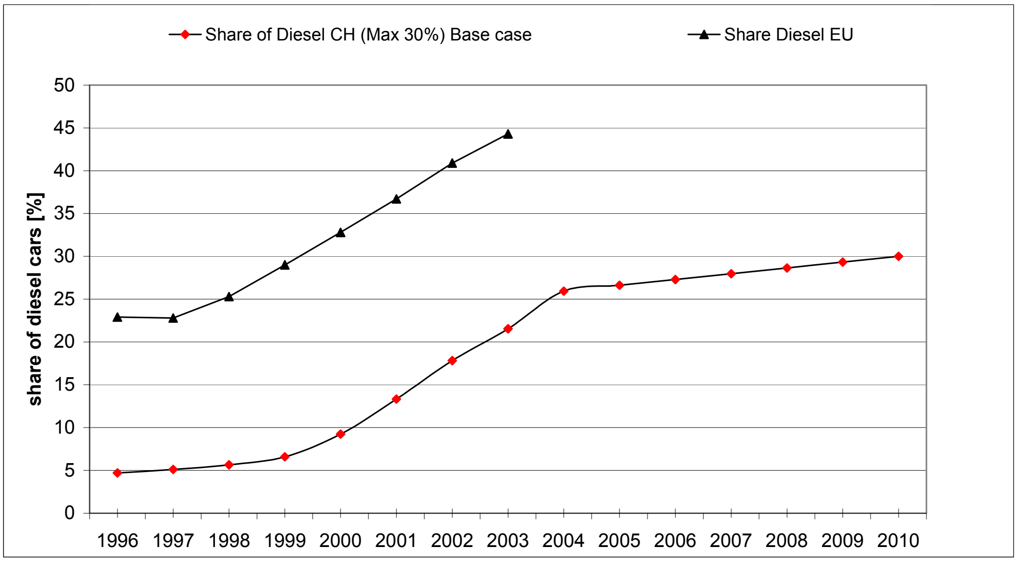

Fig. 21-1: Development of the share of diesel passenger cars among newly registered cars from 1996 up to 2010. The Swiss figures from 2004 onward are extrapolations based on the assumption that in 2010 diesel passneger cars will have a share of 30%.

As far as fuel consumption – and directly coupled CO_2-emissions – are concerned, the average figures of newly registered cars in Switzerland are considerably higher than the European average (see Fig. 21-2).

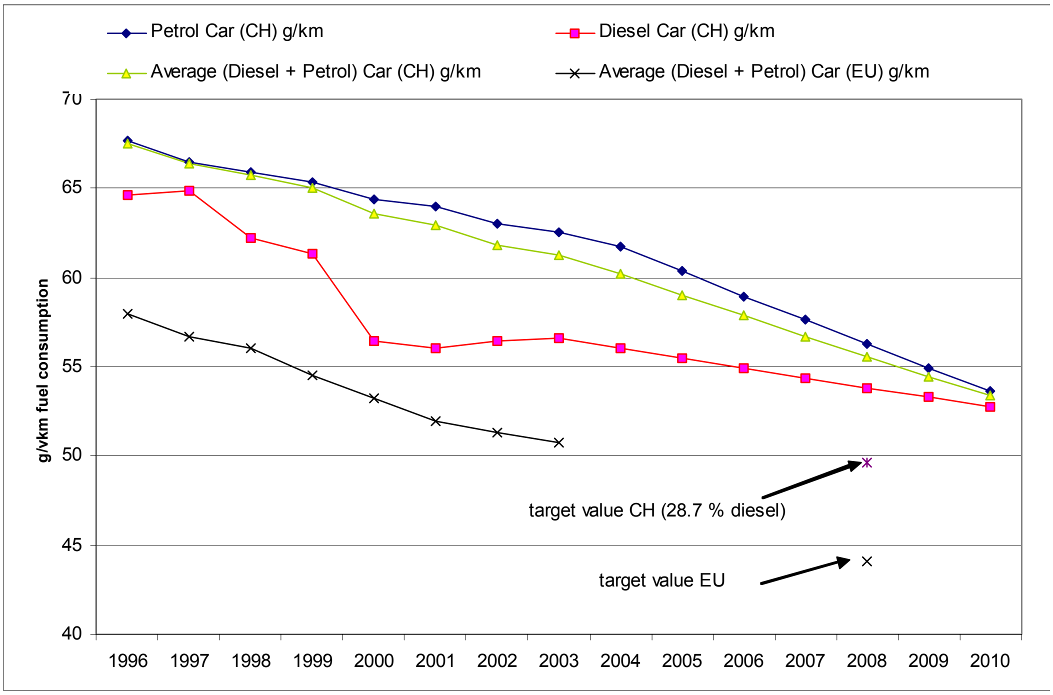

Fig. 21-2: Development of fuel consumption in recent years. The figures from 2004 onward are extrapolations based on the assumption of a yearly reduction rate of 2%. (Spielmann & Althaus 2006)

The reasons for this are manifold, e.g. the low share of diesel vehicles and the high share of vehicles with higher engine capacity and power etc. According to the target agreement between the Swiss association of car importers (auto-schweiz) and the Federal Department of the Environment, Transport, Energy and Communications a yearly reduction rate (2000 – 2008) of fuel consumption of 3% is required to match the target of 6.4 litres/100km in 2008 (auto-schweiz 2004). However, the average yearly reduction in the last eight years (1996-2004) was about 1.7%. This reduction rate is considerably below the target value.

21.3 Use of Passenger Car Services

Car transportation usually serves various purposes. In Tab. 21.1 the use of a passenger car by an average Swiss traveller allocated to four commonly distinguished travel purposes is summarised. In addition to car use, the travel time expenditures for various additional, frequently used transport modes are illustrated. The figures represent the daily travel time of an average Swiss traveller with various means of transportation with respect to four different travel purposes.

Tab. 21.1: Modal Split with respect to time for an average Swiss traveller per day (Spielmann et al. 2006)

		Commuting $^{1)}$	Leisure $^{2)}$	Shopping $^{3)}$	Business $^{4)}$	Total per Mode
Pedestriant	min/person	5.80	20.62	4.62	0.69	31.73
Bycicle	min/person	1.53	2.68	0.50	0.12	4.83
Car	min/person	10.83	18.02	5.96	3.56	38.37
Motorbike	min/person	0.35	0.39	0.10	0.07	0.91
Local Public Road Tran	min/person	2.62	1.88	0.88	0.29	5.67
Coach	min/person	0.08	0.43	0.00	0.03	0.54
Train	min/person	2.20	2.02	0.51	0.28	5.01
Aircraft	min/person	0.01	0.05	0.00	0.01	0.06
Others	min/person	1.22	2.30	0.23	1.12	4.87
Share of travel purpose	min/person	24.65	48.44	12.76	6.16	91.98

1: Commuting mobility has been derived by aggregating the original categories available from (ARE & SFSO 2000) and includes the following original categories: working trips (100%), education trips (100%) and escort and service trips (25%)

2: Leisure mobility includes leisure trips (100%) and escort and service trips (25%)

3: Shopping mobility includes shopping trips (100%) and escort and service trips (25%)

4: Business mobility includes business activities (100%), travelling on company business (100%) and escort and service trips (25%)

21.4 Life Cycle Inventories for the Operation of Diesel and Petrol Passenger Cars

21.4.1 System Characteristics

Since 1996 the European emission limits for newly registered road vehicles (Euro standards) also is effective in Switzerland. Euro3 and Euro4 came into force in January 2001 and January 2006, respectively. Furthermore, we assume that the currently discussed Euro 5 (EU 2005) standard will come into force in 2010.

Simultaneously with the stepwise reduction of exhaust pollutants, a continuous reduction of the fuel consumption of the fleet of new registered cars has been agreed on (see section 21.2). For fuel-consumption a fixed yearly reduction rate is assumed; i.e. the fuel consumption will depend on the selected reference year. For each dataset generated in this project, figures for fuel consumption and regulated pollutants are matched by using the year of introduction of the Euro-emission standard as the reference year and applying the corresponding, calculated fuel consumption for the selected reference year (see. Tab. 21.2).

Tab. 21.2: Reference years for passenger car datasets and corresponding fuel consumption. For instance, let us consider the dataset "operation, passenger car, petrol, EURO4". This dataset represents a petrol car, complying with Euro4 emission standards, penetrating the market in the year 2006. This year is considered as the reference year for the corresponding dataset. Thus, figures for fuel consumption – and hence CO2-emissions – represent the situation in 2006.

ecoinvent dataset	Emission standard	Reference years for dataset and corresponding fuel consumption
operation, passenger car, petrol, EURO3	Euro 3	2005 1)
operation, passenger car, petrol, EURO4	Euro 4	2006
operation, passenger car, petrol, EURO5	Euro 5	2010
operation, passenger car, diesel, EURO3	Euro 3	2005 1)
operation, passenger car, diesel, EURO4	Euro 4	2006
operation, passenger car, diesel, EURO5	Euro 5	2010

1: Euro3 became effective already in 2001. In this study, however, we assume a Euro 3 is purchased in 2005, and hence apply the average fuel consumption for the year 2005 for these datasets.

Transport datasets "operation of a vehicle" are related to life cycles of other products and using the reference unit of [vkm].

Vehicle operation contains all processes directly connected with the operation of the vehicles, i.e., tail pipe (exhaust) emissions and emissions due to tyre abrasion. In the context of ecoinvent database, environmental impacts due to pre-combustion processes are also included, with a link to petrol/diesel supply.

21.4.2 Fuel Consumption

Measurements made with the New European Driving Cycle (NEDC) have been applied for fuel consumption figures. This test cycle is performed on a chassis dynamometer and consists of a cold start, an urban driving, and an extra-urban driving part. It is used for emission certification of light duty vehicles in Switzerland and in the European Community. Thus, emission factors of passenger cars refer to a legislative driving cycle. As demonstrated above, figures for average fuel consumption for the fleet of newly registered Swiss petrol and diesel cars are available up to the year 2004 from auto-schweiz (2004). For the required projection – up to 2010 – of the average fuel consumption of the fleet of new registered cars, we assume a yearly reduction factor of RF= 2% (Keller & Zbinden 2004; TREMOVE 2005). This reduction factor describes the fuel consumption of an average passenger car (FC_i) for certain years i between 2005 and 2010. As demonstrated in equation 1 the average fuel consumption for the fleet of newly registered Swiss petrol and diesel cars is a result of the development of three key parameters:

- average fuel consumption of newly registered diesel powered passenger cars (FCD_i)
- average fuel consumption of newly registered petrol powered passenger cars (FCP_i) and
- the share of diesel powered cars (w_D) in the reference year i.

$$FC_i = FCP_i * (1-w_D) + FCD_i * w_D \qquad (1)$$

For these three key parameters no further specifications are presented in auto-schweiz (2004). In general, to what extent either fuel type can contribute to the overall reduction is based on technological improvements, the market penetration of such improvements as well as on customer preferences with respect to engine size and vehicle weight. For the share of diesel we assume a constant yearly increase from 25% in 2004 up to 30% for the year 2010 (see Tab. 21.3).

To allow for a distinction between diesel cars and petrol cars, we have to agree on a reduction factor for one vehicle concept.

In this research we assume that the reduction rate of a Swiss average diesel car is limited to 1% (referred to the weight in kg and hence taking into account the different density of petrol and diesel fuels). This value represents the reduction from 2003 to 2004 that took place despite a slight increase in vehicle weight and the introduction of diesel vehicles with particle filters. For the near future we assume that this trend will continue. As a consequence of this assumption, a higher reduction rate for petrol cars is required to match the overall reduction target. This is in line with the generally assumed different focus of improvements for petrol cars and diesel cars. For petrol cars the focus is a further fuel consumption reduction, whilst for diesel cars the focus is on particle emission reduction (TREMOVE 2005).

Tab. 21.3 Fuel Consumption of diesel and petrol powered engines in the time period from 2005 to 2010. The presented figures are linear projections based on a reported fuel consumption for the year 2004: average Swiss diesel car: 56.03 g/vkm and average Swiss passenger car (Diesel and Petrol): 60.25 g/vkm. It should be noted that the presented figures are not yet corrected with respect to carbon emissions due to other carbon-containing emissions.

Year		2005	2006	2007	2008	2009	2010
Emission Standard		Euro3	Euro4				Euro5
		i=1	i=2	i=3	i=4	i=5	i=6
Diesel Share (w_D)	%	26.62	27.29	27.97	28.65	29.32	30.00
Fuel Consumption Swiss Average FC_i	g/vkm	59.04	57.86	56.70	55.57	54.46	53.37
Fuel Consumption Petrol Car ($FCP_{,i}$)	g/vkm	**60.34**	**58.97**	**57.61**	**56.27**	**54.95**	**53.64**
Fuel Consumption Diesel Car ($FCD_{,i}$)	g/vkm	**55.47**	**54.91**	**54.36**	**53.82**	**53.28**	**52.75**

21.4.3 Fuel Quality and Fuel Consumption Dependent Emissions

Carbon dioxide and sulphur dioxide emissions are directly derived from the fuel consumption and carbon content or sulphur content of the used fuel, respectively.

In Tab. 21.4 the calculated emissions are summarised. For the determination of CO_2-emissions we employ a conversion factor of 3.175 kg_{CO2}/kg_{Fuel} for either fuel type. For SO_2-emissions we assume a sulphur content of $50mg_S/kg_{fuel}$ (ecoinvent fuel properties). It should be noted, that in Keller (2004) different conversion factor are presented: 0.02 g_{SO2}/kg_{diesel} (0.001 w.%) and 0.016 g_{SO2}/kg_{petrol} (0.0008 w.%), for diesel and petrol powered cars, respectively.

Tab. 21.4 CO_2-emissions and SO_2-emissions from diesel and petrol powered engines in the time period from 2005 to 2010. The presented figures are linear projections based on a reported fuel consumption for the year 2004.

Year		2005	2006	2007	2008	2009	2010
Emission Standard		Euro3	Euro4				Euro5
Diesel Share (w_D)	%	26.62	27.29	27.97	28.65	29.32	30.00
CO_2-emissions Swiss Average FC_i	g/vkm	187.46	183.71	180.04	176.44	172.91	169.45
CO_2-emissions Swiss Average Petrol Car	**g/vkm**	**191.58**	**187.22**	**182.92**	**178.67**	**174.46**	**170.29**
CO_2-emissions Swiss Average Diesel Car	**g/vkm**	**176.11**	**174.35**	**172.61**	**170.88**	**169.17**	**167.48**
SO_2-emissions Swiss Average FC_i	g/vkm	5.90E-03	5.79E-03	5.67E-03	5.56E-03	5.45E-03	5.34E-03
SO_2-emissions Swiss Average Petrol Car	**g/vkm**	**6.03E-03**	**5.90E-03**	**5.76E-03**	**5.63E-03**	**5.49E-03**	**5.36E-03**
SO_2-emissions Swiss Average Diesel Car	**g/vkm**	**5.55E-03**	**1.11E-03**	**1.10E-03**	**1.09E-03**	**1.08E-03**	**1.07E-03**

21.4.4 Regulated Emissions and Further Specifications

For Switzerland, comprehensive data for regulated pollutants (HC, CO, NO_x and particles) are available from various sources. In Keller (2004), Figures for Euro2 and Euro3 cars are derived from real world test-bench cycles. The obtained emission factors are directly based on bag data obtained from these real world driving cycles, or on linear combinations of the results of these cycles. These figures differ from emission quantities derived from the type approval cycles (NEDC) applied in bioenergy TP1a for the calculation of passenger cars powered with alternative fuels.

In order to be consistent with these datasets and to allow for a comparison of various alternative fuel concepts with conventional fuels, emission factors for regulated emissions in this project are based on the New European Driving Cycle (NEDC).

For Euro4 cars, no measurements have been performed, yet. In order to determine emission scores for Euro4 passenger cars we apply reduction factors derived from de Haan (2004). In Tab. 21.5 these factors are summarised

Tab. 21.5: Reduction Factors (RF) for the change from Euro3 to Euro4 passenger cars (derived from de Haan (2004))

Euro3 --> Euro4	Urban	Rural	Motorway	**Average 1)**
Diesel				
CO	16.7%	16.7%	16.7%	**16.7%**
HC	16.7%	16.7%	16.7%	**16.7%**
Nox	33.3%	33.3%	33.3%	**33.3%**
PM	50.3%	50.3%	50.3%	**50.3%**
Petrol				
CO	28.6%	28.6%	12.5%	**23.2%**
HC	33.3%	33.3%	28.6%	**31.7%**
Nox	33.3%	33.3%	25.0%	**30.5%**
PM	0.0%	0.0%	0.0%	**0.0%**

1: used in this project

EURO 5 emission factors are employed as available from a recent EU proposal (EU 2005). As a matter of fact HC-emissions and NO_x-emissions of many petrol powered vehicles sold today are comfortably beneath the proposed Euro5 emission limit. In such cases, we apply the values for Euro4 vehicles. For diesel vehicles, the strict emission limits of particle emissions will require the introduction of particle filters for the entire Swiss diesel fleet.

In Tab. 21.6 and Tab. 21.7 the quantities of Euro-regulated exhaust emissions and CO_2-emissions for diesel and petrol powered engines as employed in this project are summarised. Moreover, the official Euro emission limits and literature data are presented.

Tab. 21.6: Emission factors of Euro-regulated exhaust emissions and CO_2-emissions for petrol powered passenger cars.

	Petrol Euro3					**Petrol Euro4**				**Petrol Euro5**	
Data Sorce	Euro target value	NEDC 1)	BUWAL 355 2)	de Haan 3)	**this study 4)**	Euro target value	BUWAL 355 2)	de Haan 3)	**this study 4)**	Euro target value 5)	**this study 4)**
Emissions	kg/vkm	kg/vkm	kg/vkm	kg/vkm	**kg/vkm**	kg/vkm	kg/vkm	kg/vkm	**kg/vkm**	kg/vkm	**kg/vkm**
CO	2.20E-03	9.84E-04	1.52E-03	1.04E-03	**9.84E-04**	1.00E-03	2.30E-04	8.45E-04	**7.55E-04**	7.55E-04	**7.55E-04**
Nox	1.50E-04	5.13E-05	4.00E-05	5.50E-05	**5.13E-05**	8.00E-05	4.00E-05	3.80E-05	**3.56E-05**	6.00E-05	**3.56E-05**
PM (exh) Tot.	-	2.00E-06	2.00E-06	-	**2.00E-06**	-	-	-	**2.00E-06**	2.00E-06	**2.00E-06**
HC	2.00E-04	9.59E-05	7.00E-05	1.60E-05	**9.59E-05**	1.00E-04	6.00E-05	1.10E-05	**6.55E-05**	7.50E-05	**6.55E-05**
CO_2	-	1.97E-01	2.03E-01	-	**1.92E-01**	-	2.01E-01		**1.87E-01**		**1.70E-01**

1: derived from Kljun (2007)

2: Keller (2004): real world driving cycles values for 2005. Data include, cold start emissions, evaporation of hydrocarbons, ageing effects of catalytic converter.

3: de Haan (2004): real world driving cycles values for 2005; exclusively warm emissions.

4: quantities of regulated emissions for Euro4 cars are based on emissions of Euro3 cars, representing the NEDC.

5: Euro5 emission limits are derived from EU (2005). For NO_x and HC-emissions, Euro4 measures are already below the thresholds introduced in the Euro5 proposal.

Tab. 21.7: Emission factors of Euro-regulated exhaust emissions and CO_2-emissions for diesel powered passenger cars.

	Diesel Euro3					Diesel Euro4				Diesel Euro5	
Data Sorce	Euro target value	NEDC 1)	BUWAL 355 2)	de Haan 3)	**this study 4)**	Euro target value	BUWAL 355 2)	de Haan 3)	**this study 4)**	Euro target value 5)	**this study 4)**
Emissions	kg/vkm	kg/vkm	kg/vkm	kg/vkm	**kg/vkm**	kg/vkm	kg/vkm	kg/vkm	**kg/vkm**	kg/vkm	**kg/vkm**
CO	6.40E-04	6.10E-04	2.50E-04	1.62E-04	**6.10E-04**	5.00E-04	2.30E-04	1.35E-04	**5.09E-04**	-	5.09E-04
NOx	5.00E-04	5.18E-04	4.90E-04	5.13E-04	**5.18E-04**	2.50E-04	3.30E-04	3.42E-04	**3.45E-04**	2.00E-04	2.00E-04
PM (exh) Tot.	5.00E-05	3.42E-05	3.60E-05	3.30E-05	**3.42E-05**	2.50E-05	1.80E-05	1.60E-05	**1.70E-05**	5.00E-06	5.00E-06
HC	-	1.37E-04	7.00E-05	4.10E-05	**1.37E-04**	-	6.00E-05	3.50E-05	**1.14E-04**	-	1.14E-04
CO_2	-	1.73E-01	1.84E-01	-	**1.76E-01**	-	1.80E-01	-	**1.74E-01**	-	1.67E+02

1: derived from Kljun (2007)

2: Keller (2004): real world driving cycles values for 2005. Data include, cold start emissions, evaporation of hydrocarbons, ageing effects of catalytic converter.

3: de Haan (2004): real world driving cycles values for 2005; exclusively warm emissions.

4: quantities of regulated emissions for Euro4 cars are based on emissions of Euro3 cars, representing the NEDC.

5: Euro5 emission limits are derived from EU (2005).

Specific hydrocarbon emissions have been calculated for selected species. In Tab. 21.8 the split – i.e. the contribution of each species to the overall HC score – used in this project and the resulting exhaust emissions are summarised. In line with ecoinvent methodology, the values listed here for NMHC do not include emission of benzene, toluene and xylene.

Tab. 21.8: Specific hydrocarbon exhaust emissions and applied profiles for either concept. The last two columns present the applied contribution of each species to the overall HC score.

	Petrol			**Diesel**			**Petrol**	**Diesel**
	Euro3	**Euro4**	**Euro5**	**Euro3**	**Euro4**	**Euro5**	**Split**	**Split**
	kg/vkm	kg/vkm	kg/vkm	kg/vkm	kg/vkm	kg/vkm	%	%
NMHC	6.74E-05	4.04E-05	4.04E-05	1.30E-04	1.1E-04	1.1E-04	61.7%	95.3%
Methane	5.42E-06	5.50E-06	5.50E-06	3.28E-06	2.7E-06	2.7E-06	8.4%	2.4%
Benzene	6.86E-06	8.47E-06	8.47E-06	1.81E-06	1.3E-06	1.3E-06	12.9%	1.2%
Toluene	8.87E-06	6.09E-06	6.09E-06	4.38E-07	3.6E-07	3.6E-07	9.3%	0.3%
Xylene	7.39E-06	5.04E-06	5.04E-06	1.09E-06	9.1E-07	9.1E-07	7.7%	0.8%

Additionally to the above emissions, environmental impact due to evaporation of fuels (soak, diurnal evaporation) is also considered. For diesel powered cars, however, emissions due to evaporation are too small to be measured. Thus, environmental exchanges due to evaporation are only considered for petrol powered passenger cars (see Tab. 21.9).

Tab. 21.9: Non-exhaust emission factors due to evaporation

	Petrol
	kg/km
NMHC	5.29E-05
Methane	0.00E+00
Benzene	4.23E-07
Toluene	1.59E-06
Xylene	5.29E-07

In line with derived from Kljun (2007) also Polycyclic Aromatic Hydrocarbons (PAHs) are accounted for. Values for diesel cars (0.7E-9 kg/vkm for a direct injection concept) and petrol cars (0.4E-09kg/vkm) are taken from EMEP/CORINAIR (2005). Whilst the uncertainty of the emission factor for diesel cars is reported to be low (0.3-1.0E-9 kg/vkm), the average emission factor presented for petrol concepts is fairly high (0.001-8.8E-09 kg/vkm). Thus we adjusted the uncertainty factor for the latter concept.

PM10-emissions are further split into fine (PM2.5) and coarse (aerodynamic diameter between 2.5 and 10 µm). The size distribution is derived from Spielmann (2004). In Tab. 21.10 the resulting particle exhaust emissions are summarised.

Tab. 21.10: Particle exhaust emissions and applied mixes.

	Petrol			**Diesel**			**Petrol**	**Diesel**
	Euro3	**Euro4**	**Euro5**	**Euro3**	**Euro4**	**Euro5**	**Split**	**Split**
	kg/vkm	kg/vkm	kg/vkm	kg/vkm	kg/vkm	kg/vkm	%	%
PM < 2.5	1.78E-06	1.78E-06	1.78E-06	3.04E-05	1.51E-05	4.44E-06	88.8%	88.8%
PM 2.5-10	1.48E-07	1.48E-07	1.48E-07	2.54E-06	1.26E-06	3.71E-07	7.4%	7.4%
PM>10	7.60E-08	7.60E-08	7.60E-08	1.30E-06	6.46E-07	1.90E-07	3.8%	3.8%
Total	2.00E-06	2.00E-06	2.00E-06	3.42E-05	1.70E-05	5.00E-06	100.0%	100.0%

In addition to particle emissions from the exhaust, particles are produced from tyre abrasion, break wear and road abrasion. Spielmann (2004) gives an overview of the kind and quantities of these non-exhaust particle emissions. Since these emission factors do not depend on the type of fuel consumed, the values reported in Spielmann (2004) were adopted for the present study and applied on each vehicle concept (see Tab. 21.11)

Tab. 21.11: Non-exhaust particle emissions of passenger cars due to tyre abrasion, break wear and road abrasion (adopted from Spielmann (2004)).

PM2.5 (fine)	kg/vkm	6.70E-06
Coarse	kg/vkm	1.34E-05
TSP - PM10 (large)	kg/vkm	7.80E-05

21.4.5 Non-Regulated Emissions

In addition, to regulated emissions and further specifications of these emissions, emissions of N_2O and NH_3 are determined. These figures are derived from data available in Keller (2004). In Tab. 21.12 the employed quantities for the various concepts are summarised.

Tab. 21.12: N2O and NH3 emission factors.

	Euro3	**Euro4**	**Euro5**
N_2O	kg/vkm	kg/vkm	kg/vkm
Petrol	2.66E-06	1.33E-06	1.33E-06
Diesel	5.61E-06	5.61E-06	5.61E-06
NH_3	kg/vkm	kg/vkm	kg/vkm
Petrol	2.61E-05	2.31E-05	2.31E-05
Diesel	1E-06	1E-06	1E-06

Airborne heavy metal (HM) emissions due to trace elements in fuels and tyres are also accounted for and summarised in Tab. 21.13. In addition, heavy metal emissions – from tyre abrasion – to water and soil are recorded, as reported in Spielmann (2004).

Tab. 21.13: Airborne heavy metal emissions (Note correct unit g HM/vkm)

	Trace elments in fuels		**Tyre Abrasion**
	Diesel	Petrol	
	(kg_{HM}/kg_{Fuel})	(kg_{HM}/kg_{Fuel})	kg_{HM}/vkm
Cadmium	1.00E-08	1.00E-08	7.29E-07
Copper	1.70E-06	1.70E-06	1.09E-05
Chromium	4.99E-08	4.99E-08	6.56E-06
Nickel	7.00E-08	7.00E-08	5.83E-06
Selenium	1.00E-08	1.00E-08	-
Zinc	1.00E-06	1.00E-06	5.85E-04
Lead	1.10E-10	2.00E-08	3.65E-06
Mercury	2.00E-11	7.00E-11	-
Chromium VI	1.00E-10	1.00E-10	-

21.5 Life Cycle Inventories of ETBE-Blended Petrol Cars

21.5.1 System Characteristics

ETBE can provide an option to use ethanol in petrol as an alternative to direct ethanol blending. In general, the use of ethanol produces an oxygenated fuel that improves the anti-knock performance. The main advantage of ETBE over ethanol as a petrol component is its low vapour pressure (Concawe 2005; UBA 2003). Ethanol can be used as a substitute to methanol to produce ETBE (Ethyl-Tertiary-Butyl Ether) which has very similar properties to MTBE (Methyl Tertiary Butyl Ether). MTBE is a high octane blending component for petrol and was widely used in US petrol until groundwater contamination issues led to it being withdrawn in some areas. In Europe, MTBE was introduced as one of the measures to recover octane after phasing out of lead in petrol (Concawe 2005). In Switzerland, in 2005 „Bleifrei-95-Benzin“ had an average MTBE content of 3.7 Vol.% and „Bleifrei-98“ an average MTBE content of 10.7 Vol. % (Interek 2006).

The European Union Directive 98/70 relating to the quality of petrol and diesel fuels authorises the incorporation of ETBE in petrol in any proportion up to 15 Vol.% (Dörmer et al. 2005). In this research we investigate two options: 4 Vol.% and 15 Vol.%.

21.5.2 Fuel Consumption

In line with Concawe (2005), it was assumed that for blends of a conventional base fuel (in this case petrol) with an alternative fuel (in this case ETBE) the fuel consumption on energy basis would remain the same as for the base fuel. In other words the quantity of ETBE above the substituted quantity of MTBE are deemed not to have any effect positive or negative on the energy efficiency of the engine (tank to wheel) efficiency.

However, the substitution of some of the petrol with oxygenated petrol will lower passenger cars' tank to wheel efficiency with respect to the required mass or volume of fuel because oxygenates contain less energy than conventional petrol. The production of ETBE/gasoline blend 15 Vol.% is described in chapter 16.12. In line with the properties ETBE/gasoline blends we apply a lower heating value (LHV) of 41.5 kg/MJ and 42.4 kg/MJ, for a 15 Vol.% and 4 Vol% blend. The resulting calculated fuel consumption for either blend is illustrated in Tab. 21.14.

Tab. 21.14: Fuel demand and underlying assumptions for Petrol/ETBE 15 passenger cars

Fuel Type		Petrol low sulphur	Petrol/ETBE 15	Petrol/ETBE 4
Technology		average newly registered car in 2006 EURO4 (NEDC)		
Fuel Efficiency (energy)	MJ/km	2.51E+00	2.51E+00	2.51E+00
Lower Heating Value (LHV)	MJ/kg	42.50	41.51	42.24
Fuel Efficiency (mass)	kg/km	5.90E-02	6.04E-02	5.93E-02

21.5.3 Emissions

Reuter (1992) studied European petrol oxygenated with MTBE, ETBE and ethanol and found that the emissions of oxygenated petrol are independent of the oxygenate that is used. Thus, a replacement of 3.7% MTBE with 4% bio-ETBE does not result in a change of exhaust emission patterns of petrol fuelled cars.

Assuming an ETBE content of 15Vol.% – in addition to a pure substitution of MTBE with ETBE – a certain amount of ETBE is also available for the substitution of petrol. In literature, engine-out emissions of carbon monoxide, as well as emissions of benzene and toluene are reported to be reduced for petrol fuels with oxygenated additives compared to fuels without oxygenated additives (Poulopoulos & Philippopoulos 2000; Poulopoulos et al. 2001; Reuter et al. 1992). This effect, however, is reported to be diminished after full catalytic activity (typically three way catalyst) had been achieved (Poulopoulos et al. 2001).

Consequently, in this research we assume that the magnitude of regulated emissions and emissions of related species of petrol fuelled passenger cars blended with an ETBE proportion of 15 Vol.% complying with Euro4 emission standard do not change compared to a passenger car fuelled with petrol and a lower concentration of oxygenated additives (MTBE).

Carbon dioxide and sulphur dioxide emissions are directly derived from the fuel consumption and carbon content or sulphur content of the used fuel, respectively.

For the determination of CO_2-emissions we employ a conversion factor of 3.08 and 3.15 kg_{CO2}/kg_{Fuel} for a 15 Vol.% and 4 Vol.% gasoline/ETBE blend, respectively. For SO_2-emissions we assume a sulphur content of 42.5 mg_S/kg_{fuel}.

The biogenic share of emissions of CO, CO_2 and CH_4 has been determined based on the biogenic carbon content of the fuel due to the share of ethanol in ETBE (4.38% and 1.14% biogenic carbon content for a 15 Vol.% and 4 Vol.% gasoline/ETBE blend, respectively). In Tab. 21.15 the resulting figures are presented.

Tab. 21.15: Biogenic and fossil emissions of carbon monoxide, carbon dioxide and methane for a 15 Vol.% and 4 Vol.% gasoline/ETBE blend

	15 Vol.% ETBE	4 Vol.% ETBE
	$kg_{emission}/vkm_{Petrol/ETBE15}$	$kg_{emission}/vkm_{Petrol/ETBE4}$
CO_2 (tot)	1.86E-01	1.87E-01
CO_2 (fossil)	1.78E-01	1.85E-01
CO_2 (biogenic)	8.14E-03	2.13E-03
CO (tot)	7.55E-04	7.55E-04
CO (fossil)	7.22E-04	7.47E-04
CO (biogenic)	3.31E-05	8.63E-06
CH_4 (tot)	5.50E-06	5.50E-06
CH_4 (fossil)	5.26E-06	5.44E-06
CH_4 (biogenic)	2.41E-07	6.29E-08
CO_2 (corr)	1.85E-01	1.86E-01
CO_2 (fossil)	1.77E-01	1.83E-01
CO_2 (biogenic)	8.09E-03	2.12E-03

Airborne emissions of heavy metals, based on trace elements in the fuel have been adjusted to represent the petrol/ETBE mix (chapter 16.12, properties table for ETBE).

21.5.4 Unit Process Raw Data

Tab. 21.16:Unit process raw data of the operation of diesel passenger cars.

	Name	Location	InfrastructureProcess	Unit	operation, passenger car, diesel, EURO3	operation, passenger car, diesel, EURO4	operation, passenger car, diesel, EURO5	Uncertainty	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				km	km	km			
Products	operation, passenger car, diesel, EURO3	CH	0	km	1					
	operation, passenger car, diesel, EURO4	CH	0	km		1.00E+0				
	operation, passenger car, diesel, EURO5	CH	0	km			1.00E+0			
technosphere	diesel, low-sulphur, at regional storage	CH	0	kg	5.55E-2	5.49E-2	5.27E-2	1	1.07	(2,1,1,1,1,1); own calculations, based on NEDC
gaseous fuel dependent airborne emissions	Carbon dioxide, fossil	-	-	kg	1.75E-1	1.74E-1	1.67E-1	1	1.07	(2,1,1,1,1,1); own calculations, based on fuel consumption
	Carbon dioxide, biogenic	-	-	kg	0	0	0	1	1.07	(2,1,1,1,1,1);
	Sulfur dioxide	-	-	kg	5.55E-6	1.11E-6	1.07E-6	1	1.12	(3,3,1,1,1,1); own calculations, based on fuel consumption
Process specific airborne emissions	Carbon monoxide, fossil	-	-	kg	6.10E-4	5.09E-4	5.09E-4	1	5.01	(2,3,1,1,1,2); same value as for Euro4 car
	Carbon monoxide, biogenic	-	-	kg	0	0	0	1	5.01	(2,3,1,1,1,2);
	Nitrogen oxides	-	-	kg	5.18E-4	3.45E-4	2.00E-4	1	1.51	(2,3,1,1,1,2); emission limit of Euro5 proposal
Particles (Exhaust & Non exhaust)	Particulates, > 10 um	-	-	kg	7.93E-5	7.86E-5	7.82E-5	1	1.54	(3,3,3,1,1,2); includes exhaust- and abrasions emissions. (exhaust emissions representing emission limits of Euro5 proposal)
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.59E-5	1.47E-5	1.38E-5	1	2.03	(3,3,3,1,1,2); includes exhaust- and abrasions emissions. (exhaust emissions representing emission limits of Euro5 proposal)
	Particulates, < 2.5 um	-	-	kg	3.71E-5	2.18E-5	1.11E-5	1	3.03	(3,3,3,1,1,2); includes exhaust- and abrasions emissions. (exhaust emissions representing emission limits of Euro5 proposal)
Hydrocarbons	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.30E-4	1.08E-4	1.08E-4	1	1.51	(2,3,1,1,1,2); derived from HC values; split available from HBEFA. Quantity includes evaporation.
	Methane, fossil	-	-	kg	3.28E-6	2.73E-6	2.73E-6	1	1.51	(2,3,1,1,1,2); derived from HC values; split available from HBEFA.
	Methane, biogenic	-	-	kg	0	0	0	1	1.51	(2,3,1,1,1,2);
	Benzene	-	-	kg	1.81E-6	1.33E-6	1.33E-6	1	1.51	(2,3,1,1,1,2); derived from HC values; split available from HBEFA. Quantity includes evaporation em.
	Toluene	-	-	kg	4.38E-7	3.64E-7	3.64E-7	1	1.51	(2,3,1,1,1,2); derived from HC values; split available from HBEFA. Quantity includes evaporation em.
	Xylene	-	-	kg	1.09E-6	9.11E-7	9.11E-7	1	1.51	(2,3,1,1,1,2); derived from HC values; split available from HBEFA. Quantity includes evaporation em.
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	7.00E-10	7.00E-10	7.00E-10	1	12.01	(2,3,1,1,1,2); rough estimate, derived from corinair (direct injection concept)
Others	Dinitrogen monoxide	-	-	kg	5.61E-6	5.61E-6	5.61E-6	1	1.53	(2,3,1,1,1,4); derived from HC values; split available from HBEFA. Quantity includes evaporation em.
	Ammonia	-	-	kg	1.00E-6	1.00E-6	1.00E-6	1	1.24	(2,3,1,1,1,4); derived from HC values; split available from HBEFA. Quantity includes evaporation em.
Heavy metals	Cadmium	-	-	kg	1.28E-9	1.28E-9	1.26E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Copper	-	-	kg	1.05E-7	1.04E-7	1.01E-7	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium	-	-	kg	9.33E-9	9.30E-9	9.19E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Nickel	-	-	kg	9.71E-9	9.68E-9	9.52E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Selenium	-	-	kg	5.55E-10	5.49E-10	5.27E-10	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Zinc	-	-	kg	6.41E-7	6.40E-7	6.38E-7	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Lead	-	-	kg	3.65E-9	3.65E-9	3.65E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Mercury	-	-	kg	1.11E-12	1.10E-12	1.05E-12	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium VI	-	-	kg	5.55E-12	5.49E-12	5.27E-12	1	5.42	(4,5,5,1,1,5); own calculation
	Heat, waste	-	-	MJ	2.52E+0	2.49E+0	2.39E+0	1	1.22	(2,1,1,1,1,5); own calculation; based on HHV.
Emissions to water	Lead	-	-	kg	1.44E-8	1.44E-8	1.44E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium, ion	-	-	kg	2.89E-9	2.89E-9	2.89E-9	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper, ion	-	-	kg	4.33E-8	4.33E-8	4.33E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium, ion	-	-	kg	2.60E-8	2.60E-8	2.60E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel, ion	-	-	kg	2.31E-8	2.31E-8	2.31E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc, ion	-	-	kg	2.32E-6	2.32E-6	2.32E-6	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
Emissions to soil	Lead	-	-	kg	1.44E-8	1.44E-8	1.44E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium	-	-	kg	2.89E-9	2.89E-9	2.89E-9	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper	-	-	kg	4.33E-8	4.33E-8	4.33E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium	-	-	kg	2.60E-8	2.60E-8	2.60E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel	-	-	kg	2.31E-8	2.31E-8	2.31E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc	-	-	kg	2.32E-6	2.32E-6	2.32E-6	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition

Tab. 21.17: Unit process raw data of the operation of petrol passenger cars.

	Name	Location	InfrastructureProcess	Unit	operation, passenger car, petrol, EURO3	operation, passenger car, petrol, EURO4	operation, passenger car, petrol, EURO5	Uncertainty	StandardDeviation95%	GeneralComment
	Location				CH	CH	CH			
	InfrastructureProcess				0	0	0			
	Unit				km	km	km			
Products	operation, passenger car, petrol, EURO3	CH	0	km	1					
	operation, passenger car, petrol, EURO4	CH	0	km		1.00E+0				
	operation, passenger car, petrol, EURO5	CH	0	km			1.00E+0			
technosphere	petrol, low-sulphur, at regional storage	CH	0	kg	6.03E-2	5.90E-2	5.36E-2	1	1.07	(2,1,1,1,1,1); own calculations, based on NEDC
gaseous fuel dependent airborne emissions	Carbon dioxide, fossil	-	-	kg	1.90E-1	1.86E-1	1.69E-1	1	1.07	(2,1,1,1,1,1); own calculations, based on fuel consumption
	Carbon dioxide, biogenic	-	-	kg	0	0	0	1	1.07	(2,1,1,1,1,1);
	Sulfur dioxide	-	-	kg	6.03E-6	5.90E-6	5.36E-6	1	1.12	(3,3,1,1,1,1); own calculations, based on fuel consumption
Process specific airborne emissions	Carbon monoxide, fossil	-	-	kg	9.84E-4	7.55E-4	7.55E-4	1	5.01	(2,3,1,1,1,2); same value as for Euro4 car
	Carbon monoxide, biogenic	-	-	kg	0	0	0	1	5.01	(2,3,1,1,1,2);
	Nitrogen oxides	-	-	kg	5.13E-5	3.56E-5	3.56E-5	1	1.51	(2,3,1,1,1,2); target value of Euro5 proposal
Particles (Exhaust & Non exhaust)	Particulates, > 10 um	-	-	kg	7.81E-5	7.81E-5	7.81E-5	1	1.54	(3,3,3,1,1,2); includes exhaust- and abrasions emissions.
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.35E-5	1.35E-5	1.35E-5	1	2.03	(3,3,3,1,1,2); includes exhaust- and abrasions emissions.
	Particulates, < 2.5 um	-	-	kg	8.48E-6	8.48E-6	8.48E-6	1	3.03	(3,3,3,1,1,2); includes exhaust- and abrasions emissions.
Hydrocarbons	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.20E-4	9.33E-5	9.33E-5	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	Methane, fossil	-	-	kg	5.42E-6	5.50E-6	5.50E-6	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	Methane, biogenic	-	-	kg	0	0	0	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	Benzene	-	-	kg	7.28E-6	8.89E-6	8.89E-6	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	Toluene	-	-	kg	1.05E-5	7.68E-6	7.68E-6	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	Xylene	-	-	kg	1.05E-5	7.68E-6	7.68E-6	1	1.51	(2,3,1,1,1,2); derived from HC Euro5 target value; split available from HBEFA. Quantity includes evaporation.
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	4.00E-10	4.00E-10	4.00E-10	1	12.01	(2,3,1,1,1,2); rough estimate, derived from corinair
Others	Dinitrogen monoxide	-	-	kg	2.66E-6	1.33E-6	1.33E-6	1	1.53	(2,3,1,1,1,4); literature data
	Ammonia	-	-	kg	2.61E-5	2.31E-5	2.31E-5	1	1.24	(2,3,1,1,1,4); literature data
Heavy metals	Cadmium	-	-	kg	1.33E-9	1.32E-9	1.27E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Copper	-	-	kg	1.14E-7	1.11E-7	1.02E-7	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium	-	-	kg	9.57E-9	9.50E-9	9.24E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Nickel	-	-	kg	1.01E-8	9.96E-9	9.59E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Selenium	-	-	kg	6.03E-10	5.90E-10	5.36E-10	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Zinc	-	-	kg	6.46E-7	6.44E-7	6.39E-7	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Lead	-	-	kg	3.65E-9	3.65E-9	3.65E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Mercury	-	-	kg	4.22E-12	4.13E-12	3.75E-12	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium VI	-	-	kg	6.03E-12	5.90E-12	5.36E-12	1	5.42	(4,5,5,1,1,5); own calculation
	Heat, waste	-	-	MJ	2.72E+0	2.66E+0	2.42E+0	1	1.22	(2,1,1,1,1,5); own calculation; based on HHV.
Emissions to water	Lead	-	-	kg	1.44E-8	1.44E-8	1.44E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium, ion	-	-	kg	2.89E-9	2.89E-9	2.89E-9	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper, ion	-	-	kg	4.33E-8	4.33E-8	4.33E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium, ion	-	-	kg	2.60E-8	2.60E-8	2.60E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel, ion	-	-	kg	2.31E-8	2.31E-8	2.31E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc, ion	-	-	kg	2.32E-6	2.32E-6	2.32E-6	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
Emissions to soil	Lead	-	-	kg	1.44E-8	1.44E-8	1.44E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium	-	-	kg	2.89E-9	2.89E-9	2.89E-9	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper	-	-	kg	4.33E-8	4.33E-8	4.33E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium	-	-	kg	2.60E-8	2.60E-8	2.60E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel	-	-	kg	2.31E-8	2.31E-8	2.31E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc	-	-	kg	2.32E-6	2.32E-6	2.32E-6	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition

Tab. 21.18: Unit process raw data of the operation of a petrol/ETBE15 passenger car.

	Name	Location	InfrastructureProcess	Unit	operation, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	operation, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH	CH			
	InfrastructureProcess				0	0			
	Unit				km	km			
	operation, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	CH	0	km	1.00E+0	0			
	operation, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	CH	0	km	0	1.00E+0			
technosphere	petrol, 15% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	CH	0	kg	6.04E-2	0	1	1.07	(2,1,1,1,1,1); own calculations
technosphere	petrol, 4% vol. ETBE additive, EtOH f. biomass, prod. RER, at service station	CH	0	kg	0	5.93E-2	1	1.07	(2,1,1,1,1,1); own calculations
gaseous fuel dependent airborne emissions	Carbon dioxide, fossil	-	-	kg	0.177	1.83E-1	1	1.07	(2,1,1,1,1,1); own calculations, based on fuel consumption and fossil C-content in fuel
	Carbon dioxide, biogenic	-	-	kg	8.09E-3	2.12E-3	1	1.07	(2,1,1,1,1,1); own calculations, based on fuel consumption and biogenic C-content in fuel
	Sulfur dioxide	-	-	kg	5.13E-6	5.04E-6	1	1.12	(3,3,1,1,1,1); own calculations, based on fuel consumption and S-content in fuel
Process specific airborne emissions	Carbon monoxide, fossil	-	-	kg	7.22E-4	7.47E-4	1	5.27	(2,3,1,1,4,2); based on NEDC values of Euro4 car and fossil C-content in fuel
	Carbon monoxide, biogenic	-	-	kg	3.31E-5	8.63E-6	1	5.27	(2,3,1,1,4,2); based on NEDC values of Euro4 car and biogenic C-content in fuel
	Nitrogen oxides	-	-	kg	3.56E-5	3.56E-5	1	1.78	(2,3,1,1,4,2); based on NEDC values of Euro4 petrol car
Particles (Exhaust & Non exhaust)	Particulates, > 10 um	-	-	kg	7.81E-5	7.81E-5	1	1.81	(3,3,3,1,4,2); includes exhaust- and abrasions emissions. (exhaust emissions representing NEDC)
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.35E-5	1.35E-5	1	2.26	(3,3,3,1,4,2); includes exhaust- and abrasions emissions. (exhaust emissions representing NEDC)
	Particulates, < 2.5 um	-	-	kg	8.48E-6	8.48E-6	1	3.25	(3,3,3,1,4,2); includes exhaust- and abrasions emissions. (exhaust emissions representing NEDC)
Hydrocarbons	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.33E-5	9.33E-5	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	Methane, fossil	-	-	kg	5.26E-6	5.44E-6	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	Methane, biogenic	-	-	kg	2.41E-7	6.29E-8	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	Benzene	-	-	kg	8.89E-6	8.89E-6	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	Toluene	-	-	kg	7.68E-6	7.68E-6	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	Xylene	-	-	kg	7.68E-6	7.68E-6	1	1.78	(2,3,1,1,4,2); adopeted from Euro4 petrol car
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	4.00E-10	4.00E-10	1	12.41	(2,3,1,1,4,2); rough estimate for petrol cars derived from corineair
Others	Dinitrogen monoxide	-	-	kg	1.33E-6	1.33E-6	1	1.80	(2,3,1,1,4,4); adopeted from Euro4 petrol car
	Ammonia	-	-	kg	2.31E-5	2.31E-5	1	1.58	(2,3,1,1,4,4); adopeted from Euro4 petrol car
Heavy metals	Cadmium	-	-	kg	1.24E-9	1.23E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Copper	-	-	kg	9.82E-8	9.67E-8	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium	-	-	kg	9.13E-9	9.08E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Nickel	-	-	kg	9.42E-9	9.36E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Selenium	-	-	kg	5.13E-10	5.04E-10	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Zinc	-	-	kg	6.37E-7	6.36E-7	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Lead	-	-	kg	3.65E-9	3.65E-9	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Mercury	-	-	kg	4.23E-12	4.15E-12	1	5.42	(4,5,5,1,1,5); abrasion of tyres and trace elements in fuel
	Chromium VI	-	-	kg	6.04E-12	5.93E-12	1	5.42	(4,5,5,1,1,5); own calculation
	Heat, waste	-	-	MJ	2.72E+0	2.68E+0	1	1.22	(2,1,1,1,1,5); own calculation; based on HHV.
Emissions to water	Lead	-	-	kg	1.44E-8	1.44E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium, ion	-	-	kg	2.89E-9	2.89E-9	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper, ion	-	-	kg	4.33E-8	4.33E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium, ion	-	-	kg	2.60E-8	2.60E-8	1	3.55	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel, ion	-	-	kg	2.31E-8	2.31E-8	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc, ion	-	-	kg	2.32E-6	2.32E-6	1	5.63	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
Emissions to soil	Lead	-	-	kg	1.44E-8	1.44E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Cadmium	-	-	kg	2.89E-9	2.89E-9	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Copper	-	-	kg	4.33E-8	4.33E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Chromium	-	-	kg	2.60E-8	2.60E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Nickel	-	-	kg	2.31E-8	2.31E-8	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition
	Zinc	-	-	kg	2.32E-6	2.32E-6	1	2.11	(5,5,5,1,1,5); abrasion of tyres, quantity derived from tyre composition

21.5.5 Data Quality Considerations

For determining the uncertainty of the unit process raw data, the simplified approach with a pedigree matrix has been used to calculate the standard deviation. For all data uncertainty type=1 is used. However, in order to account for the extremely high uncertainty of PAH-emissions from petrol cars, we increased the basic uncertainty from 3 to 12.

21.6 Life Cycle Inventories of Transportation

21.6.1 System characteristics

In line with Spielmann et al. (2004), the transport datasets are related to the reference unit of one passenger kilometre [pkm]. The environmental interventions due to vehicle transport are modelled by linking the environmental interventions due to vehicle operation with impacts due to vehicle manufacturing, vehicle maintenance, vehicle disposal, road construction, operation and maintenance of roads and road disposal. So-called demand factors (see Spielmann (2005)) are used to link the transport service components to the functional unit of one passenger kilometre [pkm].

For consistency, the kilometric performance, the infrastructure data, and the demand factors for the transport components have been adopted from Spielmann et al. (2004), i.e. are derived from the ecoinvent database. It is assumed, that these factors do not depend on the type of fuel. This means that for passenger cars an average utilization of 1.59 passengers per car was assumed.

21.6.2 Unit process raw data

The applied demand factors are summarised in Tab. 20.7.

Tab. 21.19: Unit process raw data of transport processes of passenger cars.

	401	InputGroup	OutputGroup	Name	Location	InfrastructureProcess	Unit	transport, passenger car, diesel, EURO3	transport, passenger car, diesel, EURO4	transport, passenger car, diesel, EURO5	transport, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	transport, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	transport, passenger car, petrol, EURO3	transport, passenger car, petrol, EURO4	transport, passenger car, petrol, EURO5	UncertaintyType	StandardDeviation 95%	GeneralComment
	662			Location				CH	CH	CH	CH	CH	CH	CH	CH			
	493			InfrastructureProcess				0	0	0	0	0	0	0	0			
	403			Unit				pkm	pkm	pkm	pkm	pkm	pkm	pkm	pkm			
Products		-	0	transport, passenger car, diesel, EURO3	CH	0	pkm	1										
		-	0	transport, passenger car, diesel, EURO4	CH	0	pkm		1.00E+0									
		-	0	transport, passenger car, diesel, EURO5	CH	0	pkm			1.00E+0								
		-	0	transport, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	CH	0	pkm				1							
		-	0	transport, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	CH	0	pkm					1						
		-	0	transport, passenger car, petrol, EURO3	CH	0	pkm						1.00E+0					
		-	0	transport, passenger car, petrol, EURO4	CH	0	pkm							1.00E+0				
		-	0	transport, passenger car, petrol, EURO5	CH	0	pkm								1.00E+0			
technosphere		5	-	operation, passenger car, diesel, EURO3	CH	0	km	6.29E-1								1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, diesel, EURO4	CH	0	km		6.29E-1							1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, diesel, EURO5	CH	0	km			6.29E-1						1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	CH	0	km				6.29E-1					1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	CH	0	km					6.29E-1				1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, petrol, EURO3	CH	0	km						6.29E-1			1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, petrol, EURO4	CH	0	km							6.29E-1		1	2.01	(3,1,1,1,1,na); own calculations
		5	-	operation, passenger car, petrol, EURO5	CH	0	km								6.29E-1	1	2.01	(3,1,1,1,1,na); own calculations
		5	-	passenger car	RER	1	unit	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	1	3.01	(3,1,1,2,1,na); own calculations
		5	-	maintenance, passenger car	RER	1	unit	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	1	3.01	(3,1,1,2,1,na); own calculations
		5	-	disposal, passenger car	RER	1	unit	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	4.19E-6	1	3.01	(3,1,1,2,1,na); own calculations
		5	-	road	CH	1	ma	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	1	3.01	(3,1,1,1,1,na); own calculations
		5	-	operation, maintenance, road	CH	1	ma	7.39E-4	7.39E-4	7.39E-4	7.39E-4	7.39E-4	7.39E-4	7.39E-4	7.39E-4	1	3.01	(3,1,1,1,1,na); own calculations
		5	-	disposal, road	RER	1	ma	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	4.36E-4	1	3.01	(3,1,1,1,1,na); own calculations

21.6.3 Data Quality Considerations

For determining the uncertainty of the Unit process raw data, the simplified approach with a pedigree matrix has been used to calculate the standard deviation.

21.7 Cumulative Results and Interpretation

21.7.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific in-

puts from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

21.7.2 Cumulative Results of Operation of Passenger Cars

In Tab. 21.20 the cumulative results for the operation of passenger cars are summarised. Achieved reductions in exhaust emissions due to the introduction of Euro-emission standards are alleviated by constant emissions in the fuel chain. For instance, for PM2.5 emission of diesel cars, vehicle travel emissions (exhaust emissions and abrasions emissions) are reduced by a factor of 3.3 (Euro5 compared to Euro3). Taken into account the fuel chain emissions as presented in the below table, the reduction factor is reduced to 2.3.

A comparison of fossil CO_2-emissions of a Euro4 petrol car with the ETBE/petrol cars reveals slightly higher emissions for the latter, despite the fact that exhaust emissions of petrol cars are higher. Since operation-emissions include exhaust emissions and cumulative emissions of the fuel chain, lower exhaust emissions of ETBE/petrol cars are outbalanced by higher emissions in the fuel production compared with petrol-production. For NO_x-emissions – characterised by the same exhaust emissions for Euro4 petrol cars and ETBE/petrol cars – higher NO_x-emissions in the fuel production of ETBE/petrol cars result in slightly higher operation emissions.

Tab. 21.20 Selected LCI results and cumulative energy demand for passenger car operation

		Name		operation, passenger car, diesel, EURO3	operation, passenger car, diesel, EURO4	operation, passenger car, diesel, EURO5	operation, passenger car, petrol, EURO3	operation, passenger car, petrol, EURO4	operation, passenger car, petrol, EURO5	operation, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	operation, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	km	km	km	km	km	km	km	km
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.0	3.0	2.9	3.5	3.4	3.1	3.3	3.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1
LCI results											
resource	Land occupation	total	m2a	5.7E-4	5.6E-4	5.4E-4	7.9E-4	7.7E-4	7.0E-4	3.5E-2	9.8E-3
air	Carbon dioxide, fossil	total	kg	2.0E-1	2.0E-1	1.9E-1	2.3E-1	2.3E-1	2.1E-1	2.2E-1	2.3E-1
air	NMVOC	total	kg	2.6E-4	2.4E-4	2.3E-4	3.1E-4	2.8E-4	2.6E-4	2.5E-4	2.5E-4
air	Nitrogen oxides	total	kg	6.5E-4	4.7E-4	3.2E-4	2.1E-4	2.0E-4	1.8E-4	2.0E-4	1.8E-4
air	Sulphur dioxide	total	kg	1.8E-4	1.7E-4	1.6E-4	3.0E-4	2.9E-4	2.6E-4	3.4E-4	3.5E-4
air	Particulates, < 2.5 um	total	kg	4.7E-5	3.1E-5	2.0E-5	2.2E-5	2.1E-5	2.0E-5	2.4E-5	2.2E-5
water	BOD	total	kg	5.8E-4	5.7E-4	5.5E-4	7.3E-4	7.1E-4	6.5E-4	8.9E-4	9.2E-4
soil	Cadmium	total	kg	2.9E-9	2.9E-9	2.9E-9	2.9E-9	2.9E-9	2.9E-9	1.5E-8	6.2E-9
Further LCI results											
air	Carbon dioxide, biogenic	total	kg	4.6E-7	4.5E-7	4.4E-7	-2.2E-6	-2.2E-6	-2.0E-6	-8.5E-5	-2.6E-5
air	Carbon dioxide, land transformation	low population density	kg	4.6E-7	4.5E-7	4.4E-7	5.3E-7	5.2E-7	4.7E-7	1.1E-6	6.9E-7
air	Methane, biogenic	total	kg	3.5E-8	3.4E-8	3.3E-8	4.6E-8	4.5E-8	4.1E-8	7.8E-8	5.8E-8
air	Carbon monoxide, biogenic	total	kg	2.5E-7	2.4E-7	2.3E-7	3.3E-7	3.2E-7	2.9E-7	3.4E-5	9.0E-6

In Tab. 21.21 the cumulative results for the transport of passenger cars are summarised. Transport of passenger cars includes car operation, car manufacturing, maintenance and disposal, as well as road infrastructure construction, maintenance and disposal. Clearly, the lower vehicle operation emissions, the higher the relative contribution of the remaining components. For instance, NOx-emissions due to operation of a Euro3 diesel car contribute to 82.1% of the total cumulative transport emission score. A further reduction of NO_x-emissions due to the introduction of Euro5-emission standards results in a considerably lower contribution of 70%.

Tab. 21.21 Selected LCI results and cumulative energy demand for passenger car Transport

		Name		transport, passenger car, diesel, EURO3	transport, passenger car, diesel, EURO4	transport, passenger car, diesel, EURO5	transport, passenger car, petrol, EURO3	transport, passenger car, petrol, EURO4	transport, passenger car, petrol, EURO5	transport, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	transport, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	pkm	pkm	pkm	pkm	pkm	pkm	pkm	pkm
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	2.4	2.4	2.3	2.7	2.7	2.5	2.6	2.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
LCI results											
resource	Land occupation	total	m2a	7.7E-3	7.7E-3	7.7E-3	7.8E-3	7.8E-3	7.8E-3	3.0E-2	1.3E-2
air	Carbon dioxide, fossil	total	kg	1.6E-1	1.5E-1	1.5E-1	1.7E-1	1.7E-1	1.6E-1	1.7E-1	1.7E-1
air	NMVOC	total	kg	2.3E-4	2.2E-4	2.1E-4	2.6E-4	2.4E-4	2.3E-4	2.2E-4	2.2E-4
air	Nitrogen oxides	total	kg	4.9E-4	3.8E-4	2.9E-4	2.2E-4	2.1E-4	2.0E-4	2.1E-4	2.0E-4
air	Sulphur dioxide	total	kg	2.4E-4	2.3E-4	2.3E-4	3.1E-4	3.1E-4	2.9E-4	3.4E-4	3.5E-4
air	Particulates, < 2.5 um	total	kg	4.2E-5	3.3E-5	2.6E-5	2.7E-5	2.6E-5	2.6E-5	2.8E-5	2.7E-5
water	BOD	total	kg	4.5E-4	4.5E-4	4.3E-4	5.5E-4	5.4E-4	4.9E-4	6.5E-4	6.6E-4
soil	Cadmium	total	kg	1.9E-9	1.9E-9	1.9E-9	1.9E-9	1.9E-9	1.9E-9	9.7E-9	3.9E-9
Further LCI results											
air	Carbon dioxide, biogenic	total	kg	-9.9E-5	-9.9E-5	-9.9E-5	-1.0E-4	-1.0E-4	-1.0E-4	-1.5E-4	-1.2E-4
air	Carbon dioxide, land transformation	low population density	kg	1.0E-6	1.0E-6	9.8E-7	1.0E-6	1.0E-6	1.0E-6	1.4E-6	1.1E-6
air	Methane, biogenic	total	kg	2.3E-7	2.3E-7	2.2E-7	2.3E-7	2.3E-7	2.3E-7	2.5E-7	2.4E-7
air	Carbon monoxide, biogenic	total	kg	1.5E-5	1.5E-5	1.5E-5	1.5E-5	1.5E-5	1.5E-5	3.6E-5	2.0E-5

21.8 Abreviations and Glossary

Abreviations

ETBE	Ethyl-Tertiary-Butyl Ether
MTBE	Methyl Tertiary Butyl Ether
NEDC	New European Driving Cycle
NMHC	Non Methane HydroCarbons (often presented as NMVOC)
Vol.%	Percentage volume
w.%	Percentage weight

Glossary

oxygenated fuel	An oxygenated fuel, for instance oxygenated petrol is a mixture of conventional petrol and one or more combustible liquids which contain oxygen ("oxygenates"). At present, the most common oxygenates are ethanol and MTBE (methyl tertiary-butyl ether).
oxygenates	combustible liquids which contain oxygen
Petrol/ETBE 15	petrol blended with 15 Vol.% ETBE
Euro3,4,5	European emission limits for passenger vehicles

21.9 References

(ACEA 2004) ACEA (2004) Final reports: Monitoring of ACEA's commitment on CO2 emission reductions from passenger cars. European Automobile Manufacturers Association and Commission Services, Brussels.

(ARE & SFSO 2000) ARE and SFSO (2000) Data files of the travel behaviour microcensus.

(auto-schweiz 2004) auto-schweiz (2004) 9. Berichterstattung im Rahmen der Energieverordnung über die Absenkung des spezifischen Treibstoff-Normverbrauchs von Personenwagen 2004. Vereinigung Schweizer Automobil-Importeure., Bern.

(Carle 2005) Carle G. (2005) Erdgasfahrzeuge im Wettbewerb. ETHZ-IVT, Zurich.

(Concawe 2005) Concawe (2005) Well-to-wheels analysis of future automotive fuels and powertrains in the european context. Report Version 2a, December 2005. European Comission, Joint Research Centre.

(de Haan & Keller 2004) de Haan P. and Keller M. (2004) Emission Factors for passenger cars and light-duty vehicles, Bern.

(Dörmer et al. 2005) Dörmer W., Neumann N. and Schlaab J. (2005) Betriebsstoffe. In: Handbuch Verbrennungsmotor (Ed. van Basshysen R. and Schäfer F.). Vieweg, Wiesbaden.

(EMEP/CORINAIR 2005) EMEP/CORINAIR (2005) An approach to estimate PAH emissions. In: EMEP/CORINAIR Emission Inventory Guidebook - 2005 (Ed. Agency E. E.). European Environment Agency, Copenhagen.

(EU 2005) EU (2005) Clean cars: Commission proposes to reduce emissions., Vol. IP/05/1660 (ed. EU). European Community Commission Services, Brussels, retrieved from: http://europa.eu.int/rapid/pressReleasesAction.do?reference=IP/05/1660&format=HTML&aged=0&language=DE&guiLanguage=en.

(Interek 2006) Interek C. B. (2006) Eigenschaften der in der Schweiz im Jahre 2005 im Interteklabor untersuchten handelsüblichen Benzine.

(Keller & Zbinden 2004) Keller M. and Zbinden P. (2004) Pollutant emissions from road transport 1980 - 2030. Publised by the Swiss Agency for the environment, forests and landscapes. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.

(Keller et al. 2004) Keller M., Zbinden R. and de Haan P. (2004) Handbook emission factors for road transport. v 2.1. UBA Berlin/ UBA Wien/ BUWAL Bern.

(Kljun & Keller 2007) Kljun N. and Keller M. (2007) Road transport services biofuels and alternative fuels. In: Life Cycle Inventories of Bioenergy (Ed. Jungbluth N.). ecoinvent centre, Uster.

(Pehnt 2003) Pehnt M. (2003) Assessing future energy and transport systems: The case of fuel cells. Part 2: Environmental Performance. In: Int J of LCA, 8(6), pp. 365-378.

(Poulopoulos & Philippopoulos 2000) Poulopoulos S. and Philippopoulos C. (2000) Influence of MTBE addition into gasoline on automotive exhaust emissions. In: Atmospheric Environment, 34(28), pp. 4781, retrieved from: http://www.sciencedirect.com/science/article/B6VH3-41360TY-V/2/769b41016b6f87609a5022ee6aee8b15.

(Poulopoulos et al. 2001) Poulopoulos S. G., Samaras D. P. and Philippopoulos C. J. (2001) Regulated and unregulated emissions from an internal combustion engine operating on ethanol-containing fuels. In: Atmospheric Environment, 35(26), pp. 4399, retrieved from: http://www.sciencedirect.com/science/article/B6VH3-43J6T5X-3/2/18d21f70dab748bad21eae850bb4e03e.

(Reuter et al. 1992)	Reuter M., Benson J. D., Burns V., Gorse R., Hochhauser A. M., Koelh W., Painter W., Rippon B. and Rutherford J. (1992) Effects of oxygenated fuels and RVP on automotive emissions. Auto-oil improvement program. In: SAE technical paper 920326, pp.
(Spielmann et al. 2004)	Spielmann M., Kägi T., Stadler P. and Tietje O. (2004) Life cycle inventories of transport services. Final report ecoinvent 2000 No. 14. UNS, ETH-Zurich, Swiss Centre for Life Cycle Inventories, Duebendorf, CH, retrieved from: www.ecoinvent.ch.
(Spielmann & Scholz 2005)	Spielmann M. and Scholz R. W. (2005) Life Cycle Inventories for Transport Services - Background Data for Freight Transport. In: Int J LCA, 10(1), pp.
(Spielmann & Althaus 2006)	Spielmann M. and Althaus H.-J. (2006) Can a prolonged car use of a passenger car reduce environmental burdens? Life cycle analysis of Swiss passenger cars. In: Journal of Cleaner Production, accepted, pp.
(Spielmann et al. 2006)	Spielmann M., de Haan P. and Scholz R. W. (2006) Induced Environmental Impacts and Rebound Effects in the Environmental Assessment of New High Speed Transport. In proceedings from: 2nd International Conference on Quantified Eco-Efficiency Analysis for Sustainability, Egmond aan Zee, The Netherlands, 28-30.June 2006.
(TREMOVE 2005)	TREMOVE (2005) TREMOVE 2.30 Model and Baseline Description. Final Report, D. ENV. European Commission.
(UBA 2003)	UBA (2003) Einsatz von Biokraftstoffen und deren Einfluss auf dioe Treibhausgas-Emissionen in Österreich. Umweltbundesamt GmbH, Wien.
(WBCSD 2004)	WBCSD (2004) Mobility 2030: Meeting the challenges to sustainability. World Business Council for Sustainable Development, Geneva, Switzerland.

Appendices: EcoSpold Meta Information

A1: Meta information operation diesel passenger cars

ReferenceFunction	401	Name	operation, passenger car, diesel, EURO3	operation, passenger car, diesel, EURO4	operation, passenger car, diesel, EURO5
Geography	662	Location	CH	CH	CH
ReferenceFunctio	493	InfrastructureProcess	0	0	0
ReferenceFunctio	403	Unit	km	km	km
DataSetInformatio	201	Type	1	1	1
	202	Version	1.0	1.0	1.0
	203	energyValues	0	0	0
	205	LanguageCode	en	en	en
	206	LocalLanguageCode	de	de	de
DataEntryBy	302	Person	59	59	59
	304	QualityNetwork	1	1	1
ReferenceFunctio	400	DataSetRelatesToProduct	1	1	1
	402	IncludedProcesses	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre abrasion are included.	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre abrasion are included.	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre abrasion are included.
	404	Amount	1	1	1
	490	LocalName	Betrieb, Pkw, Diesel, EURO3	Betrieb, Pkw, Diesel, EURO4	Betrieb, Pkw, Diesel, EURO5
	491	Synonyms			
	492	GeneralComment	Average data for the operation of a newly registered Euro3 car in Switzerland in the year 2005.	Average data for the operation of a newly registered Euro4 car in Switzerland in the year 2006.	Average data for the operation of a newly registered Euro5 car in Switzerland in the year 2010.
	494	InfrastructureIncluded	1	1	1
	495	Category	transport systems	transport systems	transport systems
	496	SubCategory	road	road	road
	497	LocalCategory	Transportsysteme	Transportsysteme	Transportsysteme
	498	LocalSubCategory	Strasse	Strasse	Strasse
	499	Formula			
	501	StatisticalClassification			
	502	CASNumber			
TimePeriod	601	StartDate	2005	2006	2010
	602	EndDate	2005	2006	2010
	603	DataValidForEntirePeriod	1	1	1
	611	OtherPeriodText	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.
Geography	663	Text	Data refer to Swiss Conditions	Data refer to Swiss Conditions	Data refer to Swiss Conditions
Technology	692	Text	Diesel, Euro3	Diesel, Euro4	Diesel, Euro5
Representativene	722	Percent	100	100	100
	724	ProductionVolume	not known	not known	not known
	725	SamplingProcedure	Literature data.	Literature data.	Literature data.
	726	Extrapolations	none	none	none
	727	UncertaintyAdjustments	none	none	none
DataGeneratorAn	751	Person	59	59	59
	756	DataPublishedIn			
	757	ReferenceToPublishedSource	40	40	40
	758	Copyright	1	1	1
	759	AccessRestrictedTo	0	0	0
	760	CompanyCode			
	761	CountryCode			
	762	PageNumbers			

A2: Meta information operation petrol passenger cars

ReferenceFunction	401	Name	operation, passenger car, petrol, EURO3	operation, passenger car, petrol, EURO4	operation, passenger car, petrol, EURO5
Geography	662	Location	CH	CH	CH
ReferenceFunctio	493	InfrastructureProcess	0	0	0
ReferenceFunctio	403	Unit	km	km	km
DataSetInformatio	201	Type	1	1	1
	202	Version	1.0	1.0	1.0
	203	energyValues	0	0	0
	205	LanguageCode	en	en	en
	206	LocalLanguageCode	de	de	de
DataEntryBy	302	Person	59	59	59
	304	QualityNetwork	1	1	1
ReferenceFunctio	400	DataSetRelatesToProduct	1	1	1
	402	IncludedProcesses	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Hydrocarbon emissions include evaporation. Heavy metal emissions to soil and water caused by tyre abrasion are included.	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Hydrocarbon emissions include evaporation. Heavy metal emissions to soil and water caused by tyre abrasion are included.	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Hydrocarbon emissions include evaporation. Heavy metal emissions to soil and water caused by tyre abrasion are included.
	404	Amount	1	1	1
	490	LocalName	Betrieb, Pkw, Benzin, EURO3	Betrieb, Pkw, Benzin, EURO4	Betrieb, Pkw, Benzin, EURO5
	491	Synonyms			
	492	GeneralComment	Average data for the operation of a newly registered Euro3 car in Switzerland in the year 2005.	Average data for the operation of a newly registered Euro4 car in Switzerland in the year 2006.	Average data for the operation of a newly registered Euro5 car in Switzerland in the year 2010.
	494	InfrastructureIncluded	1	1	1
	495	Category	transport systems	transport systems	transport systems
	496	SubCategory	road	road	road
	497	LocalCategory	Transportsysteme	Transportsysteme	Transportsysteme
	498	LocalSubCategory	Strasse	Strasse	Strasse
	499	Formula			
	501	StatisticalClassification			
	502	CASNumber			
TimePeriod	601	StartDate	2005	2006	2010
	602	EndDate	2005	2006	2010
	603	DataValidForEntirePeriod	1	1	1
	611	OtherPeriodText	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.
Geography	663	Text	Data refer to Swiss Conditions	Data refer to Swiss Conditions	Data refer to Swiss Conditions
Technology	692	Text	Petrol, Euro3	Petrol, Euro4	Petrol, Euro5
Representativene	722	Percent	100	100	100
	724	ProductionVolume	not known	not known	not known
	725	SamplingProcedure	Literature data.	Literature data.	Literature data.
	726	Extrapolations	none	none	none
	727	UncertaintyAdjustments	none	none	none
DataGeneratorAnd	751	Person	59	59	59
	756	DataPublishedIn			
	757	ReferenceToPublishedSource	40	40	40
	758	Copyright	1	1	1
	759	AccessRestrictedTo	0	0	0
	760	CompanyCode			
	761	CountryCode			
	762	PageNumbers			

A3: Meta information operation Petrol/ETBE 15 passenger cars

ReferenceFunction	401	Name	operation, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	operation, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4
Geography	662	Location	CH	CH
ReferenceFunctio	493	InfrastructureProcess	0	0
ReferenceFunctio	403	Unit	km	km
DataSetInformatio	201	Type	1	1
	202	Version	1.0	1.0
	203	energyValues	0	0
	205	LanguageCode	en	en
	206	LocalLanguageCode	de	de
DataEntryBy	302	Person	59	59
	304	QualityNetwork	1	1
ReferenceFunctio	400	DataSetRelatesToProduct	1	1
	402	IncludedProcesses	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre abrasion are included.	Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre abrasion are included.
	404	Amount	1	1
	490	LocalName	Betrieb, Pkw, Benzin, 15% Vol. ETBE mit Ethanol aus Biomasse, EURO4	Betrieb, Pkw, Benzin, 4% Vol. ETBE mit Ethanol aus Biomasse, EURO4
	491	Synonyms		
	492	GeneralComment	Biogenic shares of CO,-CO2 and CH4 emissions are determined based on the bigenic/fossil ratio of the used fuel. Regulated emissions and related species are adopted from average data for the operation of a newly registered Euro4 car in Switzerland in the year 2006.	Biogenic shares of CO,-CO2 and CH4 emissions are determined based on the bigenic/fossil ratio of the used fuel. Regulated emissions and related species are adopted from average data for the operation of a newly registered Euro4 car in Switzerland in the year 2006.
	494	InfrastructureIncluded	1	1
	495	Category	transport systems	transport systems
	496	SubCategory	road	road
	497	LocalCategory	Transportsysteme	Transportsysteme
	498	LocalSubCategory	Strasse	Strasse
	499	Formula		
	501	StatisticalClassification		
	502	CASNumber		
TimePeriod	601	StartDate	2006	2006
	602	EndDate	2006	2006
	603	DataValidForEntirePeriod	1	1
	611	OtherPeriodText	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.
Geography	663	Text	Data refer to the Swiss conditions	Data refer to the Swiss conditions
Technology	692	Text	Petrol with 15% ETBE with EtOH from biomass, Euro4	Petrol with 4% ETBE with EtOH from biomass, Euro4
Representativene	722	Percent	100%	100%
	724	ProductionVolume	not known	not known
	725	SamplingProcedure	Literature data.	Literature data.
	726	Extrapolations	none	none
	727	UncertaintyAdjustments	none	none
DataGeneratorAn	751	Person	59	59
	756	DataPublishedIn		
	757	ReferenceToPublishedSource	40	40
	758	Copyright	1	1
	759	AccessRestrictedTo	0	0
	760	CompanyCode		
	761	CountryCode		
	762	PageNumbers		

A4: Meta information transport diesel passenger cars

ReferenceFunction	401	Name	transport, passenger car, diesel, EURO3	transport, passenger car, diesel, EURO4	transport, passenger car, diesel, EURO5
Geography	662	Location	CH	CH	CH
ReferenceFunctio	493	InfrastructureProcess	0	0	0
ReferenceFunctio	403	Unit	pkm	pkm	pkm
DataSetInformatio	201	Type	1	1	1
	202	Version	1.0	1.0	1.0
	203	energyValues	0	0	0
	205	LanguageCode	en	en	en
	206	LocalLanguageCode	de	de	de
DataEntryBy	302	Person	59	59	59
	304	QualityNetwork	1	1	1
ReferenceFunctio	400	DataSetRelatesToProduct	1	1	1
	402	IncludedProcesses	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.
	404	Amount	1	1	1
	490	LocalName	Transport, Pkw, Diesel, EURO3	Transport, Pkw, Diesel, EURO4	Transport, Pkw, Diesel, EURO5
	492	GeneralComment	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.
	494	InfrastructureIncluded	1	1	1
	495	Category	transport systems	transport systems	transport systems
	496	SubCategory	road	road	road
	497	LocalCategory	Transportsysteme	Transportsysteme	Transportsysteme
	498	LocalSubCategory	Strasse	Strasse	Strasse
	499	Formula			
	501	StatisticalClassification			
	502	CASNumber			
TimePeriod	601	StartDate	2005	2006	2010
	602	EndDate	2005	2006	2010
	603	DataValidForEntirePeriod	1	1	1
	611	OtherPeriodText	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.
Geography	663	Text	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.
Technology	692	Text	Diesel, Euro3	Diesel, Euro4	Diesel, Euro5
Representativene	722	Percent	100	100	100
	724	ProductionVolume	not known	not known	not known
	725	SamplingProcedure	Literature data.	Literature data.	Literature data.
	726	Extrapolations	none	none	none
	727	UncertaintyAdjustments	none	none	none
DataGeneratorAnd	751	Person	59	59	59
	756	DataPublishedIn			
	757	ReferenceToPublishedSource	40	40	40
	758	Copyright	1	1	1
	759	AccessRestrictedTo	0	0	0
	760	CompanyCode			
	761	CountryCode			
	762	PageNumbers			

A5: Meta information transport petrol passenger cars and Petrol/ETBE passenger cars

ReferenceFunction	401	Name	transport, passenger car, petrol, 15% vol. ETBE with ethanol from biomass, EURO4	transport, passenger car, petrol, 4% vol. ETBE with ethanol from biomass, EURO4	transport, passenger car, petrol, EURO3	transport, passenger car, petrol, EURO4	transport, passenger car, petrol, EURO5
Geography	662	Location	CH	CH	CH	CH	CH
ReferenceFunctio	493	InfrastructureProcess	0	0	0	0	0
ReferenceFunctio	403	Unit	pkm	pkm	pkm	pkm	pkm
DataSetInformatio	201	Type	1	1	1	1	1
	202	Version	1.0	1.0	1.0	1.0	1.0
	203	energyValues	0	0	0	0	0
	205	LanguageCode	en	en	en	en	en
	206	LocalLanguageCode	de	de	de	de	de
DataEntryBy	302	Person	59	59	59	59	59
	304	QualityNetwork	1	1	1	1	1
ReferenceFunctio	400	DataSetRelatesToProduct	1	1	1	1	1
	402	IncludedProcesses	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.	operation of vehicle; production, maintenance and disposal of vehicles; construction and maintenance and disposal of road.
	404	Amount	1	1	1	1	1
	490	LocalName	Transport, Pkw, Benzin, 15% Vol. ETBE mit Ethanol aus Biomasse, EURO4	Transport, Pkw, Benzin, 4% Vol. ETBE mit Ethanol aus Biomasse, EURO4	Transport, Pkw, Benzin, EURO3	Transport, Pkw, Benzin, EURO4	Transport, Pkw, Benzin, EURO5
	492	GeneralComment	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.	Inventory refers to the entire transport life cycle. For road infrastructure, expenditures and environmental interventions due to construction, renewal and disposal of roads have been allocated based on the Gross tonne kilometre performance. Expenditures due to operation of the road infrastructure, as well as land use have been allocated based on the yearly vehicle kilometre performance. For the attribution of vehicle share to the transport performance a vehicle life time performance of 2.39E05 pkm/ vehicle has been assumed.
	494	InfrastructureIncluded	1	1	1	1	1
	495	Category	transport systems	transport systems	transport systems	transport systems	transport systems
	496	SubCategory	road	road	road	road	road
	497	LocalCategory	Transportsysteme	Transportsysteme	Transportsysteme	Transportsysteme	Transportsysteme
	498	LocalSubCategory	Strasse	Strasse	Strasse	Strasse	Strasse
	499	Formula					
	501	StatisticalClassification					
	502	CASNumber					
TimePeriod	601	StartDate	2006	2006	2005	2006	2010
	602	EndDate	2006	2006	2006	2010	2010
	603	DataValidForEntirePeriod	1	1	1	1	1
	611	OtherPeriodText	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.	Year in which Euro-standard is coming into effect.
Geography	663	Text	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.	The data for vehicle operation and road infrastructure reflect Swiss conditions. Data for vehicle manufacturing and maintenance represents generic European data. Data for the vehicle disposal reflect the Swiss situation.
Technology	692	Text	15%Vol. ETBE blended petrol; Euro4 emission standard	4%Vol. ETBE blended petrol; Euro4 emission standard	Petrol, Euro3	Petrol, Euro4	Petrol, Euro5
Representativene	722	Percent	100	100	100	100	100
	724	ProductionVolume	not known	not known	not known	not known	not known
	725	SamplingProcedure	Literature data.	Literature data.	Literature data.	Literature data.	Literature data.
	726	Extrapolations	none	none	none	none	none
	727	UncertaintyAdjustments	none	none	none	none	none
DataGeneratorAnd	751	Person	59	59	59	59	59
	756	DataPublishedIn					
	757	ReferenceToPublishedSource	40	40	40	40	40
	758	Copyright	1	1	1	1	1
	759	AccessRestrictedTo	0	0	0	0	0
	760	CompanyCode					
	761	CountryCode					
	762	PageNumbers					

Part II

II.v. Waste Management Services

Authors: Gabor Doka, Doka Life Cycle Assessments, Zürich

Citation:

Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist Emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J. 2007: Life Cycle Inventories of Bioenergy. ecoinvent report No. 17, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

22 Incineration of Biowaste and Sewage Sludge

Author: Gabor Doka, Doka Life Cycle Assessments, Zürich
Review: Niels Jungbluth, ESU-services, Uster
Last changes: June 2006

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I thank Christoph Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services) for process data of the future municipal solid waste incinerator Hagenholz.

I thank Max Maurer, EAWAG Dübendorf, for expertise on Swiss wastewater treatment plants.

Summary

The life cycle inventories of the incineration of *biowaste* ("green waste") and *sewage sludge* are presented. Raw and digested sewage sludge are distinguished, i.e. before or after biogas production. Energy production in current Swiss average and one possible future *municipal solid waste incinerator* (MSWI) is recorded and presented as an multi-output dataset for disposal services and energy production. Allocation with economical parameters is applied.

Included processes are transport to incineration facility, dewatering in the case of sewage sludge, landfilling of solid remains from municipal incineration. Energy production is heeded up to the point of net output and does not include burdens of energy distribution. Functional units of disposal datasets refer to one kilogram of wet waste, i.e. for sewage sludge before dewatering. The net energy production is inventoried per megajoule for heat, and per kilowatt-hour for electricity. Inventory data are largely based on (Doka 2003).

22.1 Introduction

In this chapter 22 life cycle inventory data and the underlying assumptions for the following incineration processes are presented:

Tab. 22.1 Overview of processes in this chapter.

Incinerator plant	*Incinerated waste*	*Plant technology*
• Municipal incineration	• municipal biowaste	• current
		• future
	• digested sewage sludge	• current
		• future
	• raw sewage sludge	• current

For the purposes of this chapter, biowaste is **wet biomass waste ("green waste")** like biomass kitchen waste from food preparation, food wastes, biomass waste from gardening or park maintenance, all of which can originate either from a residence, from a business or from municipality services. This is in accord with the biowaste fraction of chapter 4 regarding biogas production. Other materials, that could be considered biowaste like e.g. waste wood, cardboard, paper, or slaughterhouse waste are not considered here.

Sewage sludge is the slurry residue from *municipal wastewater treatment*, i.e. stems from municipal sewage. Separate inventories are created describing the incineration of raw and digested sewage sludge from municipal wastewater treatment plants (WWTP). The distinction between raw and digested sludge is detailed in chapter 22.3 'Characterisation of Biowaste and Sewage Sludge'. Inventories of municipal incineration of biowaste and digested sludge are given in two variations: *current* Swiss technology (2000) and *future* technology (ca. for 2015).

22.2 Reserves and Resources of Biowaste and Sewage Sludge

For renewable materials like biomass a useful definition of the available reserves are the amounts theoretically available per year. Reserves of theoretically available biowaste in Switzerland are not a constant amount, since their generation is dependent on current population size and consumption patterns. With increasing population and increasing food abundance the amount of generated biowaste per year tends to increase. Amount of gardening waste depends on area of gardens and parks taken care of and type of management.

In 2000 an amount of 1.6 million tons of biowaste were collected and treated in Switzerland (cf. Tab. 22.3). Statistic data of the current biowaste generation tends to neglect small scale or residential sources of biowaste, which are e.g. fed to pets and other animals or composted locally; or potential biowaste, which is not managed at all (e.g. uncollected dead plant material) which remains as biomass stock and ultimately turns to humus.

Likewise reserves of sewage sludge are not a constant amount, but dependent on current population size, wastewater management and to some extent on food consumption patterns. In 2000 an amount of approximately 4 million tons of wet sewage sludge (with 203'000 tons of dry matter) were generated in Switzerland (cf. Tab. 22.4).

22.3 Characterisation of Biowaste and Sewage Sludge

As mentioned above, in this present bioenergy study biowaste means kitchen, food or gardening wastes. These types of waste typically have high water content and rather low heating value. The biowaste composition is adopted from chapter 4 with a water content of 60 w% and a lower heating value 5.1 MJ/kg.

Most sewage sludge in Switzerland is digested (fermented) sludge, i.e. has already been used to produce biogas[52]. Raw (undigested) sludge of small scale WWTP is usually digested in larger regional WWTP. In this present bioenergy study, incineration of both raw and digested sludge is inventoried separately. Fresh wastewater treatment sludge has normally a very high water content of 94 – 96 w-%. Prior to incineration the sludge is therefore mechanically dewatered to approximately 70-75% water content to reduce transport expenditures and augment fuel qualities (BUWAL 2004a:18). Dewatering can take place at the site of the WWTP or less usually at the incineration site.

The composition of raw and digested sludge is based on data from (Doka 2003) and represents a generic composition of Swiss sewage sludge. Concentrations of carbon, hydrogen and oxygen in digested sewage sludge are adjusted to a conversion rate of 45% of organic matter in fermentation according to chapter 4 of this report. Compared to raw sludge, digested sludge has 45 w% less organic matter, and accordingly an inferior heating value.

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[52] Personal communication with Max Maurer, EAWAG Dübendorf, March 5, 2002.

Tab. 22.2 Initial compositions of biomass wastes.

			Biowaste (from chapter 4)	**Digester sludge** (Doka 2003)	**Raw sewage sludge** (Doka 2003)
lower heating value	H_u	MJ/kg	5.104	-1.341	-1.202
Water content	H_2O	%	60%	95%	95%
Oxygen	O	kg/kg	0.1264	0.009473	0.01126
Hydrogen	H	kg/kg	0.02	0.002153	0.00256
Carbon	C	kg/kg	0.1624	0.01722	0.02048
Sulfur	S	kg/kg	0.001499	0.001106	0.0009309
Nitrogen	N	kg/kg	0.004	0.001675	0.002758
Phosphor	P	kg/kg	0.00113	0.001559	0.00102
Boron	B	ppm	10.24	-	-
Chlorine	Cl	ppm	4000	-	-
Bromium	Br	ppm	6	-	-
Fluorine	F	ppm	200	-	-
Iodine	I	ppm	0.055	-	-
Arsenic	As	ppm	2	0.1396	0.09143
Cadmium	Cd	ppm	0.138	0.09937	0.06498
Cobalt	Co	ppm	5	0.5729	0.3746
Chromium	Cr	ppm	8	4.331	2.832
Copper	Cu	ppm	18	19.94	13.04
Mercury	Hg	ppm	0.07	0.09937	0.06498
Manganese	Mn	ppm	4.3	18.77	12.27
Molybdenum	Mo	ppm	0.4	0.339	0.2217
Nickel	Ni	ppm	5.42	1.865	1.219
Lead	Pb	ppm	18.56	5.524	3.612
Selenium	Se	ppm	0.4998	-	-
Tin	Sn	ppm	7.996	1.422	0.9298
Vanadium	V	ppm	2.999	-	-
Zinc	Zn	ppm	58.24	54.32	35.52
Silicon	Si	ppm	39'980	2113	1382
Iron	Fe	ppm	600	9542	6239
Calcium	Ca	ppm	21'800	3586	2345
Aluminium	Al	ppm	9995	1059	692.6
Potassium	K	ppm	3500	-	-
Magnesium	Mg	ppm	2820	402.5	263.2
Sodium	Na	ppm	1500	-	-

22.4 Use of Biowaste and Sewage Sludge

In Switzerland 641’400 tons of biowaste were collected separately in 2000 (Kettler 2003). Of that, 562'800 tons were composted in large plants with capacities over 100 t/a, by open or closed windrow composting, field-edge or box composting. The remainder of 78’600 tons were anaerobically digested in thirteen fermenter plants for biogas production. An additional amount of approximately 300’000 t of biowaste is assumed to be treated by home or community composting, or in plants with a capacity below 100 t/a (estimate in Kettler 2003). An additional amount of 700'000 tons of biowaste is not collected *separately*, but disposed as (mixed) municipal solid waste, where biowaste is currently the largest fraction by weight (27 w-%). In total an amount of 1.6 million tons of biowaste are treated per year, which equates to approximately 220 kg per capita and year.

Tab. 22.3 Swiss amounts of treated biowaste in 2000.

Biowaste = Kitchen, food, and garden waste	Metric tons per year (wet mass)	source
Biowaste collected separately		
Biowaste to large scale composting only	528'200	Kettler 2003
Biowaste to small scale composting only	300'000	estimate in Kettler 2003
Biowaste to biogas production	76'530	Kettler 2003 [1]
Biowaste in municipal solid waste		
Total biowaste in municipal solid waste	700'000	[2]
Of which potentially compostable	450'000	Kettler 2003
Total Biowaste	1'604'730	

1 Agrees well with a figure of 184 TJ biogas from biowaste in 2004 (BFE 2005) and a fermentation production factor of 0.1 Nm^3 biogas per kg biowaste, and a biogas lower heating value of 24.043 MJ/Nm^3 biogas (from this study, chapter 4), resulting in 76'600 tons biowaste to fermentation per year.

2 Collected MWS in 2000: 2.588 Mio. Tons, with a share of 27% Kitchen, food, garden waste (excluding paper, cardboard fractions) (Kettler 2003).

The annual sewage sludge generation in Switzerland was 202'757 tons (dry matter) in 2000 (cf. Tab. 22.4). Per capita generation is approximately 27 kg/cap. Disposal of sewage sludge in landfills is prohibited in Switzerland since 2000. Spreading of sewage sludge on agricultural fields is completely prohibited in Switzerland as of October 2006. The target disposal practice is incineration, which increased from 59% in 2000 to 71% in 2002 (BUWAL 2004b).

Tab. 22.4 Disposal of WWT sludge in Switzerland 2000 (BUWAL 2001a)

Disposal of WWT sludge	Metric tons per year (dry matter)	w-%
Sludge to agriculture	78'357	38.6%
Liquid fertiliser	71'838	35.4%
Compost or granulate	6'519	3.2%
Sludge to incineration	119'566	59.0%
Municipal waste incineration	21'592	10.6%
Cement kiln	33'683	16.6%
Special sludge incinerator	64'291	31.7%
Sludge to landfilling	4'834	2.4%
Total	202'757	100.0%

22.5 System characterisation

In the following some of the technologies used and jointly used features of the inventoried processes are described. For each of the inventoried processes detailed inventories are presented in chapters 22.6ff.

22.5.1 Characterization of unit processes

All datasets of this chapter relate to one kilogram of waste material. Like with other waste disposal processes in the ecoinvent database, mass refers to a *wet composition* and not dry content. Biowaste has a water content of 60%, sewage sludge is assumed to have an initial water content of 95% (see Tab. 22.2 on page 630). Sewage sludge is assumed to be dewatered before incineration. The functional unit of the according datasets refers to 1 kg *wet sewage sludge* with 95% water content.

22.5.2 Sludge dewatering process description

Before incineration some of the water in sludge is usually removed, since sludge with 95% water cannot burn by itself. Sludge dewatering (or sludge drainage) is a common process in wastewater treatment plants (WWTP). The weight reduction is approximately 80% and thus transport costs are reduced. Sludge dewatering reduces the water content of sewage sludge from approximately 95% to 73%. This is usually performed by addition of flocculation agents, to help formation of large particles, followed by mechanical dewatering processes like centrifuges, belt filters (pressure filtration), or membrane filters.

Dewatering produces a liquid rich in ammonia. Approximately 20% – 40% of the nitrogen is removed from the sludge input by this route. This liquid is recycled internally into the WWT process or treated separately. Also some carbon and phosphorus compounds are removed with the dewatering liquid.

Tab. 22.5 Weight changes resulting from digestion and/or water removal for 1000 kg wet raw sludge.

Sludge Type	Water content	**Raw sludge** (wet weight)		**Digested sludge** [1] (wet weight)
Wet sludge	95%	1000 kg	→	654 kg
		↓		↓
Dewatered sludge [2]	73%	179.3 kg		117.3 kg

1 Difference to raw sludge is based on a conversion rate of 45% of organic matter to biogas (see chapter 4)

2 Difference to wet sludge is removed dewatering liquid, containing approximately 1933 ppm dry matter.

22.5.3 Municipal incineration process description

Switzerland has 28 municipal solid waste incinerator plants (MSWI) in operation in 2006. Fig. 22.1 shows a typical plant layout of a Swiss MSWI. The number in brackets in the following text refer to the numbers in that figure. The figures on the trucks give the approximate weight of solid output products, related to 100% average municipal waste input. The typical design for a MSWI plant consists of two or three incineration lines in parallel. Each incineration line is usually equipped with a grate-type furnace (8). At the end of the grate the unburnable remains are collected as slag (bottom ash, 9). The raw gas is led to an integrated steam boiler (10). The recovered heat is usually passed on to a steam turbine (24) to generate electricity. The expanded steam is sometimes directed to a district heating network or used as process steam for neighbouring industries (25).

After being cooled down in the steam boiler, the flue gas of the MSWI is then passed into an electrostatic precipitator (ESP) for fly ash separation (12). After that, a multistage wet scrubber (14) is used to eliminate harmful components of the flue gas like SO_x or HCl by washing the raw gas in a reaction tower. The scrubbing liquid is neutralised (18), heavy metals are precipitated (19) and separated as a sludge (20) in an in-house wastewater treatment facility. The treated water is usually discharged to a river. After the wet scrubber the purified flue gas enters a DeNOx installation[53] (15).

The solid residues of the incineration process are usually landfilled. Bottom ash is landfilled in separate compartments (slag compartments). Boiler ash, fly ash, scrubber sludge are solidified with cement and landfilled in a residual material landfill.

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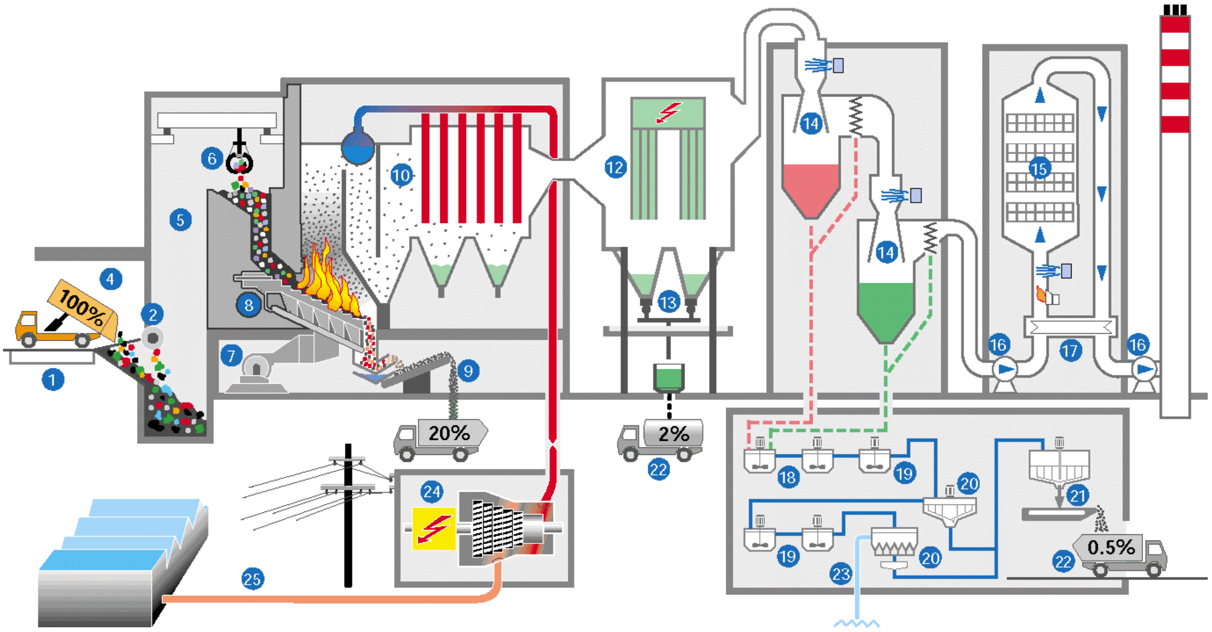
[53] Placement of the DeNOx facility depends on the technology employed: SNCR DeNOx takes place directly in the incineration chamber, SCR-high dust before the wet scrubber (i.e. in a high-dust environment), SCR-low dust after the wet scrubber (i.e. in a low-dust environment).



Waste delivery
1 scale
2 coarse refuse shredder
4 unloading bay
5 waste bunker
6 waste crane

Incinerator
7 combustion air vent
8 incinerator grate
9 slag (bottom ash) to landfill
10 steam boiler

Flue gas purification
12 electrostatic precipitator
13 electrostatic precipitator ash
14 flue gas scrubber
15 DeNOx stage (here SCR low-dust)
16 flue gas blower
17 heat recuperator

Wastewater treatment
18 neutralisation
19 precipitation
20 sedimentation
21 sludge dewatering
22 residual waste to landfill
23 purified water discharged to river

Energy conversion
24 steam turbine / generator
25 heat to district heating system

Fig. 22.1 Scheme of a typical Swiss municipal solid waste incinerator.

All 28 Swiss MSWI utilise the energy contained in the waste to produce useful heat and/or electricity. On average, the gross heat generation efficiency is 25.6% and the gross electricity generation efficiency is 13% (BUWAL 2001b). All plants consume some of the generated energy and sell the surplus energy. Net heat can be used in district heating networks or as industrial steam, depending on local circumstances.

22.5.4 General Allocation Choices

Allocation of energy production

Waste disposal processes which also generate energy are multi-functional processes: They provide the *service of waste disposal* and also generate useful energy. The question arises how much of the generated burden shall be allocated to energy products. In this present bioenergy study, the focus of interest is the *energy production function* of incinerators. An allocation with an economical key is performed, and thus a portion of the generated burdens is allocated to the produced energy[54].

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[54] In previous datasets different allocation choices were made. For waste incineration all burdens were placed on disposal and none on energy (Doka 2003:II-21ff.). The energy output from average waste incineration is not burdened, when using the default allocation scheme of (Doka 2003). Strictly speaking, the new datasets from this study are not compatible with previous datasets of the ecoinvent database, because the allocation choices are dissimilar.

Carbon balance

In this present bioenergy study, specific guidelines for assessment of carbonaceous emissions like CO_2, CO, CH_4, VOC are presented (chapter 2.6). For the datasets regarding biomass incineration presented in this chapter, a part of the CO, CH_4, VOC emissions are allocated to the generated energy using an economical allocation key. However, in deviation of the given guidelines no CO_2 uptake is inventoried in the energy datasets, which would be necessary to maintain a strict carbon balance. The resulting aberration in LCIA results is considered to be negligible. All biogenic CO_2 emissions from incineration are allocated to the *disposal process* and none to the generated energy.

22.5.5 General Data Quality Considerations

In the ecoinvent database uncertainty values of LCI exchanges are often estimated using the Pedigree approach introduced in (Frischknecht et al. 2003a).

This chapter relies on work presented in (Doka 2003). There, the exchanges in LCI raw data are usually the result of a *chain of calculations*, which depend e.g. on the composition of the waste under consideration. For example, air emissions are derived from waste composition multiplied by transfer coefficients. Also, exchanges can be derived from *sums* of several contributions, e.g. transport services for a collection of materials. Likewise, the uncertainty information of these exchanges must be *calculated* along the chain of data flow and should not be given in a static or generic manner. The basic principles of these uncertainty calculations are described in part I of (Doka 2003). The datasets of this chapter rely on the calculation tools of (Doka 2003) and therefore the principles for the calculation of uncertainty information are adopted.

The uncertainty of each element in a waste composition is estimated by a generic formula using the concentration *c* of that element. The geometric standard deviation (SDG_c) of that concentration is then given by the following expression:

$$SDG_c = N \cdot \ln(c) + 1 \qquad \text{with } N = -0.181$$

Similar formulas are applied for the uncertainty of transfer coefficients . The Pedigree approach is applied on literature data used in the calculation of LCI exchanges. In most cases, uncertainty of exchanges will not be the direct result of a Pedigree approach, but a chain of calculations. Sources of uncertainty information are documented in the description of the according datasets.

Unit process inventories in this chapter are derived from allocation procedures. The applied allocation factors are to a certain degree uncertain (uncertainty in heating values and in energy gain, uncertainty of energy revenues). The ecoinvent database software does not allow input of uncertainty factors (SDG^2) concerning allocation factors. This uncertainty could be heeded alternatively in the uncertainty factors of the allocated exchanges, but this is currently not done in ecoinvent datasets. In this study the uncertainty of allocation factors are therefore neglected as well.

22.6 Life cycle inventory of biowaste incineration in municipal waste incinerator, current

In this life cycle inventory the incineration of biowaste ('green waste') in a current municipal waste incinerator is presented. The composition of the biowaste is adopted from chapter 4, where the same waste is used for biogas production (see Tab. 22.2 on page 630).

The system boundaries comprise municipal collection and transport of the biowaste to the incinerator[55], incineration expenditures, and landfilling of solid residues. For the energy products the system cuts off after the incinerator, i.e. distribution and losses of energy by electricity grid or district heating network are not heeded.

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[55] Transport is included to comply with scope choices made in other chapters of the bioenergy study, e.g. chapter 4. In other disposal datasets of the ecoinvent database, collection and transport to the incinerator is *not* included (Doka 2003).

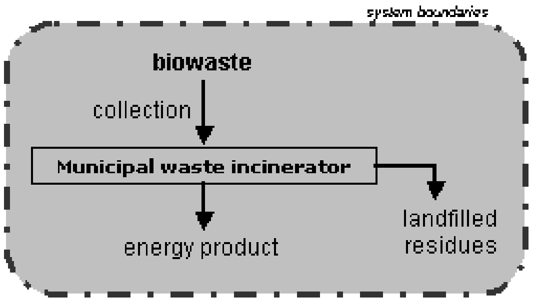

Fig. 22.2 System boundaries of biowaste incineration in municipal waste incinerator

The functional unit of the multi-output process 'biowaste, to municipal incineration' is 1 kilogram of wet biowaste with a water content of 60%. The generated unit process inventories are shown below.

Tab. 22.6 Datasets derived from the multi-output process 'biowaste, to municipal incineration'

Service function	Unit process dataset	Functional unit
disposal	disposal, biowaste, 60% H2O, to municipal incineration, allocation price	1 kg wet biowaste
net useful heat	heat, biowaste, at waste incineration plant, allocation price	1 MJ
net electricity	electricity, biowaste, at waste incineration plant, allocation price	1 kWh

Transport

A transport distance to the municipal collector of 10 km is assumed (Doka 2003). Transport with a waste collection truck is assumed.

Burdens from incineration

The incineration process is described qualitatively in chapter 22.5.3 'Municipal incineration process description' on page 632. The direct emissions from biowaste incineration of residues are calculated according to the defined elemental biowaste composition (waste-specific emissions). Exchanges of incineration and landfilling are calculated with the existing ecoinvent calculation tool for municipal waste incineration described and provided in (Doka 2003). The incinerator technology represents the Swiss average of municipal incinerators in 2000.

Energy production

The biowaste has a lower heating value of 5.1 MJ/kg$_{wet}$. The incinerator converts that energy with a gross heat generation efficiency of 25.6% and a gross electricity generation efficiency of 13%, which represents the average efficiencies of Swiss MSWI in 2000. The internal energy consumption of the waste incinerator is 0.839 MJ heat and 0.144 kWh electricity per kilogram incinerated waste (BUWAL 2001b). Thus the generated net energies from biowaste are 0.411 MJ heat and 0.145 MJ (0.04 kWh) electricity per kilogram biowaste.

Tab. 22.7 Energy generated from one kilogram of biowaste in (current) municipal waste incinerator

Biowaste lower heating value	MJ/kg	5.1	
		Heat	Electricity
Gross energy efficiency	%	25.57%	13%
Generated gross energy	MJ/kg	1.305	0.663
Internal consumption	MJ/kg	0.839	0.518
Generated net energy	MJ/kg	0.466	0.145 (0.04 kWh)

Incineration of biowaste with improved gross energy efficiencies is inventoried in chapter 22.7 'Life cycle inventory of biowaste incineration in municipal waste incinerator, future' on page 638.

Allocation

The inventoried exchanges are allocated according to the outline given in chapter 22.5.4 'General Allocation Choices' on page 633. For the allocation of disposal service vs. energy production the disposal fees and energy revenues must be known. Total disposal fees of collected Swiss municipal waste is estimated to amount to 333 million Swiss francs in 2000 (Iten et al. 2001). The total mass of collected municipal waste in 2000 was 1.663 million tons (BUWAL 2001c). Thus the Swiss average disposal fee of collected municipal waste is 0.2 CHF per kilogram waste.

The revenues of energy production in Swiss municipal incinerators are detailed in (Dettli et al. 2004:19ff). The average revenues paid to incinerator operators were 0.09 CHF per megajoule heat and 0.2628 CHF per megajoule electricity (0.073 CHF/kWh) in 2000. These values are used in the calculation of allocation factors as shown in Tab. 22.8.

Tab. 22.8 Revenues generated from one kilogram of biowaste in (current) municipal waste incinerator

Per kilogram biowaste	*Disposal service*	*Sold heat*	*Sold electricity*
Valued amounts	1 kg	0.466 MJ	0.145 MJ
Fees and prices [1]	0.2 CHF/kg	0.09 CHF/MJ	0.2628 CHF/MJ
Generated revenues	0.2 CHF	0.042 CHF	0.038 CHF
Allocation keys for this dataset	**71.39% on disposal service**	**14.97% on heat production**	**13.64% on electricity production**

1 Sources see text above.

Tab. 22.9 Unit process raw data of 'biowaste, to municipal incineration'

Explanation	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	biowaste, to municipal incineration	disposal, biowaste, 60% H2O, to municipal incineration, allocation price	heat, biowaste, at waste incineration plant, allocation price	electricity, biowaste, at waste incineration plant, allocation price	biogenic carbon content in elementary flow	biogenic carbon flow
	Location InfrastructureProcess Unit						CH 0 kg	CH 0 kg	CH 0 MJ	CH 0 kWh	kg/kg	kg/f.u.
air, high population density	Carbon monoxide, biogenic		air	high population density		kg	0.0002229	71.4	15.0	13.7	42.9%	9.55286E-05
	Carbon monoxide, fossil		air	high population density		kg	0	71.4	15.0	13.7		
	Carbon dioxide, biogenic		air	high population density		kg	0.588560537	100.0	0.0	0.0	27.3%	0.16051651
	Carbon dioxide, fossil		air	high population density		kg	0	71.4	15.0	13.7		
	Methane, biogenic		air	high population density		kg	6.38208E-06	71.4	15.0	13.7	75.0%	4.78656E-06
	Methane, fossil		air	high population density		kg	0	71.4	15.0	13.7		
	Sulfur dioxide		air	high population density		kg	6.38716E-06	71.4	15.0	13.7		
	Nitrogen oxides		air	high population density		kg	0.000127265	71.4	15.0	13.7		
	Ammonia		air	high population density		kg	3.16944E-06	71.4	15.0	13.7		
	Dinitrogen monoxide		air	high population density		kg	1.68912E-05	71.4	15.0	13.7		
	Cyanide		air	high population density		kg	3.6E-06	71.4	15.0	13.7		
	Phosphorus		air	high population density		kg	1.13E-06	71.4	15.0	13.7		
	Boron		air	high population density		kg	1.2288E-06	71.4	15.0	13.7		
	Hydrogen chloride		air	high population density		kg	4.44118E-08	71.4	15.0	13.7		
	Bromine		air	high population density		kg	1.8E-08	71.4	15.0	13.7		
	Hydrogen fluoride		air	high population density		kg	1.05263E-07	71.4	15.0	13.7		
	Iodine		air	high population density		kg	5.9391E-13	71.4	15.0	13.7		
	Silver		air	high population density		kg	0	71.4	15.0	13.7		
	Arsenic		air	high population density		kg	2.04E-14	71.4	15.0	13.7		
	Barium		air	high population density		kg	0	71.4	15.0	13.7		
	Cadmium		air	high population density		kg	7.59936E-12	71.4	15.0	13.7		
	Cobalt		air	high population density		kg	1.5875E-13	71.4	15.0	13.7		
	Chromium		air	high population density		kg	5.91527E-13	71.4	15.0	13.7		
	Copper		air	high population density		kg	1.32872E-10	71.4	15.0	13.7		
	Mercury		air	high population density		kg	2.41761E-15	71.4	15.0	13.7		
	Manganese		air	high population density		kg	2.34135E-14	71.4	15.0	13.7		
	Molybdenum		air	high population density		kg	7.99999E-10	71.4	15.0	13.7		
	Nickel		air	high population density		kg	2.3392E-13	71.4	15.0	13.7		
	Lead		air	high population density		kg	6.88925E-10	71.4	15.0	13.7		
	Antimony		air	high population density		kg	0	71.4	15.0	13.7		
	Selenium		air	high population density		kg	2.51332E-15	71.4	15.0	13.7		
	Tin		air	high population density		kg	1.06069E-08	71.4	15.0	13.7		
	Vanadium		air	high population density		kg	2.99853E-10	71.4	15.0	13.7		
	Zinc		air	high population density		kg	9.5144E-10	71.4	15.0	13.7		
	Beryllium		air	high population density		kg	0	71.4	15.0	13.7		
	Scandium		air	high population density		kg	0	71.4	15.0	13.7		
	Strontium		air	high population density		kg	0	71.4	15.0	13.7		
	Titanium		air	high population density		kg	0	71.4	15.0	13.7		
	Thallium		air	high population density		kg	0	71.4	15.0	13.7		
	Tungsten		air	high population density		kg	0	71.4	15.0	13.7		
	Silicon		air	high population density		kg	9.30761E-05	71.4	15.0	13.7		
	Iron		air	high population density		kg	2.00308E-08	71.4	15.0	13.7		
	Calcium		air	high population density		kg	3.63411E-05	71.4	15.0	13.7		
	Aluminum		air	high population density		kg	1.56142E-05	71.4	15.0	13.7		
	Potassium		air	high population density		kg	1.05521E-05	71.4	15.0	13.7		
	Magnesium		air	high population density		kg	3.88314E-06	71.4	15.0	13.7		
	Sodium		air	high population density		kg	1.4113E-05	71.4	15.0	13.7		
water, river	BOD5, Biological Oxygen Demand		water	river		kg	6.07738E-06	71.4	15.0	13.7		
	COD, Chemical Oxygen Demand		water	river		kg	1.08543E-05	71.4	15.0	13.7		
	TOC, Total Organic Carbon		water	river		kg	4.45203E-06	71.4	15.0	13.7	100.0%	4.45203E-06
	DOC, Dissolved Organic Carbon		water	river		kg	4.45203E-06	71.4	15.0	13.7		
	Sulfate		water	river		kg	0.00072797	71.4	15.0	13.7		
	Nitrate		water	river		kg	5.11647E-05	71.4	15.0	13.7		
	Phosphate		water	river		kg	2.20936E-07	71.4	15.0	13.7		
	Boron		water	river		kg	1.60153E-06	71.4	15.0	13.7		
	Chloride		water	river		kg	0.003905573	71.4	15.0	13.7		
	Bromine		water	river		kg	4.94481E-06	71.4	15.0	13.7		
	Fluoride		water	river		kg	1.5374E-05	71.4	15.0	13.7		
	Iodide		water	river		kg	5.49994E-08	71.4	15.0	13.7		
	Silver, ion		water	river		kg	0	71.4	15.0	13.7		
	Arsenic, ion		water	river		kg	9.01654E-07	71.4	15.0	13.7		
	Barium		water	river		kg	0	71.4	15.0	13.7		
	Cadmium, ion		water	river		kg	6.25853E-11	71.4	15.0	13.7		
	Cobalt		water	river		kg	8.55336E-10	71.4	15.0	13.7		
	Chromium VI		water	river		kg	2.6066E-07	71.4	15.0	13.7		
	Copper, ion		water	river		kg	7.30928E-10	71.4	15.0	13.7		
	Mercury		water	river		kg	7.48568E-10	71.4	15.0	13.7		
	Manganese		water	river		kg	2.40573E-10	71.4	15.0	13.7		
	Molybdenum		water	river		kg	6.83175E-08	71.4	15.0	13.7		
	Nickel, ion		water	river		kg	3.39948E-09	71.4	15.0	13.7		
	Lead		water	river		kg	5.17E-10	71.4	15.0	13.7		
	Antimony		water	river		kg	0	71.4	15.0	13.7		
	Selenium		water	river		kg	1.62774E-07	71.4	15.0	13.7		
	Tin, ion		water	river		kg	2.9667E-10	71.4	15.0	13.7		
	Vanadium, ion		water	river		kg	2.02326E-09	71.4	15.0	13.7		
	Zinc, ion		water	river		kg	1.07076E-08	71.4	15.0	13.7		
	Beryllium		water	river		kg	0	71.4	15.0	13.7		
	Scandium		water	river		kg	0	71.4	15.0	13.7		
	Strontium		water	river		kg	0	71.4	15.0	13.7		
	Titanium, ion		water	river		kg	0	71.4	15.0	13.7		
	Thallium		water	river		kg	0	71.4	15.0	13.7		
	Tungsten		water	river		kg	0	71.4	15.0	13.7		
	Silicon		water	river		kg	8.47198E-06	71.4	15.0	13.7		
	Iron, ion		water	river		kg	2.05326E-07	71.4	15.0	13.7		
	Calcium, ion		water	river		kg	8.24095E-05	71.4	15.0	13.7		
	Aluminum		water	river		kg	8.31683E-07	71.4	15.0	13.7		
	Potassium, ion		water	river		kg	0.000606918	71.4	15.0	13.7		
	Magnesium		water	river		kg	9.87208E-06	71.4	15.0	13.7		
	Sodium, ion		water	river		kg	0.000324292	71.4	15.0	13.7		
	Chromium, ion		water	river		kg	2.54969E-08	71.4	15.0	13.7		
water, ground-, long-term	BOD5, Biological Oxygen Demand		water	ground-, long-term		kg	0.00131088	71.4	15.0	13.7		
	COD, Chemical Oxygen Demand		water	ground-, long-term		kg	0.004007609	71.4	15.0	13.7		
	TOC, Total Organic Carbon		water	ground-, long-term		kg	0.001585821	71.4	15.0	13.7	100.0%	0.001585821
	DOC, Dissolved Organic Carbon		water	ground-, long-term		kg	0.001585821	71.4	15.0	13.7		
	Sulfate		water	ground-, long-term		kg	0.003760244	71.4	15.0	13.7		
	Nitrate		water	ground-, long-term		kg	0.000143692	71.4	15.0	13.7		
	Phosphate		water	ground-, long-term		kg	0.00013234	71.4	15.0	13.7		
	Boron		water	ground-, long-term		kg	6.74927E-06	71.4	15.0	13.7		
	Chloride		water	ground-, long-term		kg	9.43813E-05	71.4	15.0	13.7		
	Bromine		water	ground-, long-term		kg	1.04919E-06	71.4	15.0	13.7		
	Fluoride		water	ground-, long-term		kg	0.000178405	71.4	15.0	13.7		
	Iodide		water	ground-, long-term		kg	4.60038E-16	71.4	15.0	13.7		
	Silver, ion		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Arsenic, ion		water	ground-, long-term		kg	1.09834E-06	71.4	15.0	13.7		
	Barium		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Cadmium, ion		water	ground-, long-term		kg	1.38469E-09	71.4	15.0	13.7		
	Cobalt		water	ground-, long-term		kg	4.37763E-06	71.4	15.0	13.7		
	Chromium VI		water	ground-, long-term		kg	8.4688E-07	71.4	15.0	13.7		
	Copper, ion		water	ground-, long-term		kg	1.455E-05	71.4	15.0	13.7		
	Mercury		water	ground-, long-term		kg	3.64202E-09	71.4	15.0	13.7		
	Manganese		water	ground-, long-term		kg	3.70278E-06	71.4	15.0	13.7		
	Molybdenum		water	ground-, long-term		kg	3.30877E-07	71.4	15.0	13.7		
	Nickel, ion		water	ground-, long-term		kg	5.07457E-06	71.4	15.0	13.7		
	Lead		water	ground-, long-term		kg	1.32234E-06	71.4	15.0	13.7		
	Antimony		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Selenium		water	ground-, long-term		kg	3.36022E-07	71.4	15.0	13.7		
	Tin, ion		water	ground-, long-term		kg	4.01949E-06	71.4	15.0	13.7		
	Vanadium, ion		water	ground-, long-term		kg	5.14316E-07	71.4	15.0	13.7		
	Zinc, ion		water	ground-, long-term		kg	9.0294E-07	71.4	15.0	13.7		
	Beryllium		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Scandium		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Strontium		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Titanium, ion		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Thallium		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Tungsten		water	ground-, long-term		kg	0	71.4	15.0	13.7		
	Silicon		water	ground-, long-term		kg	0.003471678	71.4	15.0	13.7		
	Iron, ion		water	ground-, long-term		kg	0.000281043	71.4	15.0	13.7		
	Calcium, ion		water	ground-, long-term		kg	0.018970982	71.4	15.0	13.7		
	Aluminum		water	ground-, long-term		kg	0.00739674	71.4	15.0	13.7		
	Potassium, ion		water	ground-, long-term		kg	0.002882528	71.4	15.0	13.7		
	Magnesium		water	ground-, long-term		kg	0.002603213	71.4	15.0	13.7		
	Sodium, ion		water	ground-, long-term		kg	0.001161594	71.4	15.0	13.7		
technosphere	municipal waste incineration plant	CH	waste management	municipal incineration	1	unit	2.5E-10	71.4	15.0	13.7		
	process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	0	kg	1	71.4	15.0	13.7		
	slag compartment	CH	waste management	municipal incineration	1	unit	2.37745E-10	71.4	15.0	13.7		
	process-specific burdens, slag compartment	CH	waste management	municipal incineration	0	kg	0.133731793	71.4	15.0	13.7		
	residual material landfill facility	CH	waste management	residual material landfill	1	unit	3.92362E-11	71.4	15.0	13.7		
	process-specific burdens, residual material landfill	CH	waste management	residual material landfill	0	kg	0.018833388	71.4	15.0	13.7		
air, high population density	Heat, waste		air	high population density		MJ	5.693458659	71.4	15.0	13.7		
water, river	Heat, waste		water	river		MJ	1.498410882	71.4	15.0	13.7		
technosphere	electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	kWh	0	71.4	15.0	13.7		
	heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	MJ	0	71.4	15.0	13.7		
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	0	kg	0.004484384	71.4	15.0	13.7		
	quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.000697472	71.4	15.0	13.7		
	hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	0	kg	7.72526E-06	71.4	15.0	13.7		
	iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	7.84536E-06	71.4	15.0	13.7		
	chemicals organic, at plant	GLO	chemicals	organics	0	kg	7.04428E-07	71.4	15.0	13.7		
	chemicals inorganic, at plant	GLO	chemicals	inorganics	0	kg	1.28754E-05	71.4	15.0	13.7		
	cement, unspecified, at plant	CH	construction materials	binder	0	kg	0.007533355	71.4	15.0	13.7		
	disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	0	kg	0.018833388	71.4	15.0	13.7		
	transport, freight, rail	RER	transport systems	train	0	tkm	0.010308482	71.4	15.0	13.7		
	transport, lorry 28t	CH	transport systems	road	0	tkm	0.007285452	71.4	15.0	13.7		
	ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	0.0002018	71.4	15.0	13.7		
	natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	0	MJ	0.019679987	71.4	15.0	13.7		
	titanium dioxide, production mix, at plant	RER	chemicals	inorganics	0	kg	5.77649E-06	71.4	15.0	13.7		
	chromium oxide, flakes, at plant	RER	chemicals	inorganics	0	kg	1.17888E-07	71.4	15.0	13.7		
	transport, municipal waste collection, lorry 21t	CH	waste management	others	0	tkm	0.01	71.4	15.0	13.7		
allocated products	disposal, biowaste, 60% H2O, to municipal incineration, allocation price	CH	waste management	municipal incineration	0	kg	1	100.0	0.0	0.0	-16.2%	-0.162399893
	heat, biowaste, at waste incineration plant, allocation price	CH	waste management	municipal incineration	0	MJ	0.4664	0.0	100.0	0.0	0.0%	0
	electricity, biowaste, at waste incineration plant, allocation price	CH	waste management	municipal incineration	0	kWh	0.0405	0.0	0.0	100.0	0.0%	0
Carbon Balance	Biogenic Carbon input					kg	0.000	0.000	0.000	0.000	totals	0.000
	Biogenic Carbon output in products					kg	-0.162	-0.162	0.000	0.000		-0.162
	Biogenic Carbon emissions, except CO2					kg	0.002	0.001	0.000	0.000		0.002
	Biogenic CO2 emissions					kg	0.161	0.161	0.000	0.000		0.161
	Carbon balance (inputs - outputs)						0.000	-0.001	0.000	0.000		0.000

22.7 Life cycle inventory of biowaste incineration in municipal waste incinerator, future

In this life cycle inventory the incineration of biowaste ('green waste') in a *future* municipal waste incinerator is presented. The waste, the process, system boundary and functional units are in large parts identical to biowaste incineration in current municipal waste incinerators, presented in chapter 22.6 'Life cycle inventory of biowaste incineration in municipal waste incinerator, current' above.

The system boundaries comprise municipal collection and transport of the biowaste to the incinerator, incineration expenditures, and landfilling of solid residues. For the energy products the system cuts off after the incinerator, i.e. distribution and losses of energy by electricity grid or district heating network are not heeded.

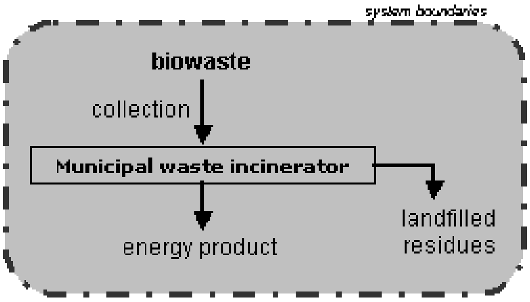

Fig. 22.3 System boundaries of biowaste incineration in future municipal waste incinerator

The functional unit of the multi-output process 'biowaste, to municipal incineration, future' is 1 kilogram of wet biowaste with a water content of 60%. The generated unit process inventories are shown below.

Tab. 22.10 Datasets derived from the multi-output process 'biowaste, to municipal incineration, future'

Service function	Unit process dataset	Functional unit
disposal	disposal, biowaste, 60% H2O, to municipal incineration, future, alloc. price	1 kg wet biowaste
net useful heat	heat, biowaste, at waste incineration plant, future, allocation price	1 MJ
net electricity	electricity, biowaste, at waste incineration plant, future, alloc. price	1 kWh

Future waste incinerator plant

The incineration process is described qualitatively in chapter 22.5.3 'Municipal incineration process description' on page 632. For this dataset, the energy production efficiency and internal energy consumption of the municipal incinerator plant have been adopted to figures of future waste incinerators. Data of a future waste incinerator is provided by Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services) for the modernised MSW incinerator Hagenholz in Zurich. This plant is being refitted and by 2010 will have augmented energy generation, with a gross thermal efficiency of 56.3% and a gross electric efficiency of 16.7%, as shown in Fig. 22.4. Other parts of Hagenholz will be modernised, e.g. furnace lines, waste bunker and scales. Also bulk metallic particles like pieces of iron, copper, brass, and aluminium will be separated from the slag prior to landfilling. For the incineration of biomass this is of no consequence, since there are no metallic particles in the residues from biomass incineration.

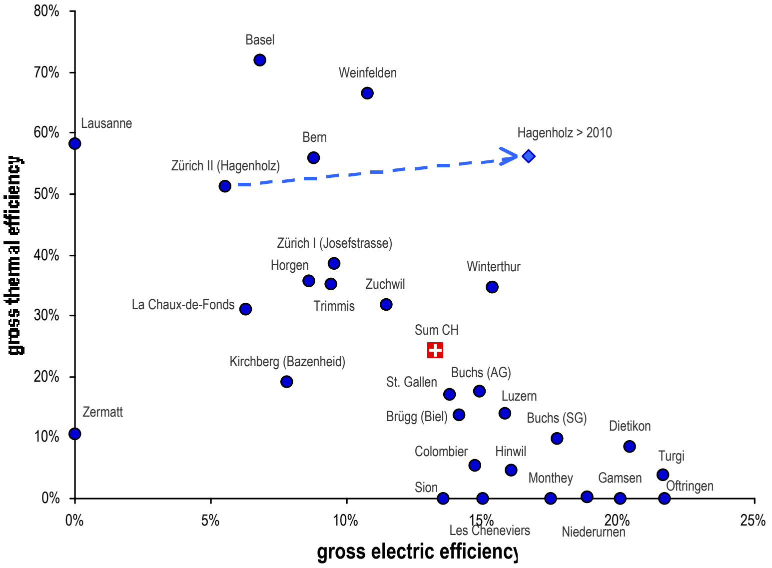

Fig. 22.4 Current gross energy efficiencies of the 28 Swiss municipal waste incinerators in 2000 and prospective efficiencies of the modernised Hagenholz plant (BUWAL 2001b).

The Swiss waste incinerators of 2000 have rather dissimilar characteristics regarding their energy production. Some plants have large heat production and little or no electricity production, like the MSWI in Lausanne (left side of Fig. 22.4); other plants show large electricity production and little heat production, for example the MSWI in Turgi (bottom of Fig. 22.4). Electricity production is popular in rural areas, where demand for district heat is rare. Similarly, the range of values for the internal energy consumption in MSWI varies greatly. In 2000, internal heat consumption ranged from 0.005 to 1 $MJ_{th.}/kg_{waste}$ and internal electricity consumption ranged from 0.36 to 1.2 $MJ_{el.}/kg_{waste}$ across the 28 Swiss MSWI plants. This range of characteristics cannot be expected to disappear in the future. The data for the future Hagenholz plant must therefore be regarded as *one possibility, not a representative future average*. Compared to the 2000 Swiss average values, the future Hagenholz plant has greatly increased thermal efficiency, and only slightly increased electric efficiency. The energy gain of the future Hagenholz plant is in the vicinity of its maximum and a further increase of e.g. electricity production likely needs to be compensated by a *decrease* in heat production (trade-off). Compared to the values for Swiss MWSI plants in 2000, the internal energy consumption figures in the future Hagenholz plant (0.099 $MJ_{th.}/kg_{waste}$; 0.36 $MJ_{el.}/kg_{waste}$) are at or beyond the lower end of this range.

Energy production

The biowaste has a lower heating value of 5.1 MJ/kg_{wet}. The future incinerator has a gross heat generation efficiency of 56.3% and a gross electric efficiency of 16.7%. The internal energy consumption of the waste incinerator is 0.099 MJ heat and 0.36 MJ electricity per kilogram waste[56]. Thus the generated net energies from one kilogram biowaste are 1.88 MJ heat and 0.492 MJ (0.137 kWh) electricity.

Some additional heat energy can be generated in the flue gas treatment by means of a heat pump and lowering of the flue gas temperature after condensation. Some of the heat energy lost to water evaporation can be regained by this route. This practice is already applied in the *current* Hagenholz plant and – stack temperatures permitting – also in other Swiss MSWI[57]. The energetic consequences – more

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[56] Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), April 3, 2006.

[57] Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), May 3, 2006.

gross heat production and more internal electricity consumption for the heat pump – are already included in the data presented in Tab. 22.11 and Tab. 22.7.

Tab. 22.11 Energy generated from one kilogram of biowaste in (future) municipal waste incinerator

Biowaste lower heating value	MJ/kg	5.1	
		Heat	Electricity
Gross energy efficiency	%	56.3%	16.7%
Generated gross energy	MJ/kg	2.87	0.852
Internal consumption	MJ/kg	0.099	0.36
Generated net energy	MJ/kg	2.77	0.492 (0.137 kWh/kg)

In a similar study on biowaste incineration, different waste-specific energy gains from biowaste were recorded, although the energy balance was also based on data for the modernised Hagenholz incinerator (ERZ 2006). The reason for this is that the internal energy consumption figures were calculated differently,[58]. Internal electricity and heat consumption was assumed to be *proportional to the lower heating value* of the waste under consideration (i.e. 0.0396 MJ/kg heat and 0.1404 MJ/kg electricity for biowaste). The lower heating value of biowaste is about 60% smaller than the lower heating value of average waste. In contrast, the values for internal energy consumption in Tab. 22.11 are *independent of heating value*; i.e. every kilogram of waste necessitates the same amount of energy consumption.

The internal energy consumption in waste incinerator plants depends on a *variety of parameters*. Specific energy consumption for waste handling, furnace loading and grate operation can be thought to be constant for every kilogram of any waste fraction. The preheating of combustion air is a major consumer of internal heat, and is high for low-calorific waste fractions. Electricity demand for flue gas blowers is a major electricity consumer, and is low for waste fractions with small specific combustion product gas volume.

In (Doka 2003), like in this study, these dependencies were not modelled, but each kilogram of waste consumed a *constant amount* of internal energy. For the case of biowaste incineration this results in a *overestimation* for the electricity demand, because the combustion product gas volume for biowaste is lower than for average waste. The internal heat demand is *underestimated*, because the heating value of biowaste is lower than for average waste and would require more energy for combustion air preheating.

On the other hand, the approach of (ERZ 2006) *underestimates* the electricity demand, since a waste fraction with zero heating value would require no internal heat at all, which is inconceivable[59]. The heat demand is *underestimated*, as waste fractions with low heating value, such as biowaste, would require *more* internal heat than average waste, not less.

To be consistent with the approach used in (Doka 2003) internal energy demands for waste incineration are modelled independently of heating value or specific flue gas volume, and are constant for every kilogram of waste.

Allocation

The inventoried exchanges are allocated according to the outline given in chapter 22.5.4 'General Allocation Choices' on page 633. Allocation factors to separate disposal service vs. energy production are based on data introduced in Tab. 22.8 on page 636. Disposal fees and electricity prices presently

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[58] Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), July 4, 2006.

[59] Also wastes without heating value require electricity demand for waste handling, furnace loading and grate operation. Waste fractions with very high water content can have *negative* heating values. The approach of (ERZ 2006) would then suggest that these waste fractions have *negative* internal electricity demand.

follow a declining trend; for heat prices no clear trend is observable, but it is probable that they will increase with rising prices for mineral oil. This inventory is for a plant in 2015. No extrapolations of prices to a future situation were attempted. The level of fees and revenues is adopted from data for the year 2000. Differences in allocation factors originate solely from different net energy gain in the MSWI.

The allocation factors applied in this dataset are shown in Tab. 22.12 below. Compared to the allocation factors in a current municipal waste incinerator (Tab. 22.8), more burdens are placed on energy products and less on disposal service. This is solely caused by increased revenues from energy production due to increased efficiencies.

Tab. 22.12 Revenues generated from one kilogram of biowaste in (future) municipal waste incinerator

Per kilogram biowaste	*Disposal service*	*Sold heat*	*Sold electricity*
Valued amounts	1 kg	2.77 MJ	0.492 MJ
Fees and prices [1]	0.2 CHF/kg	0.09 CHF/MJ	0.2628 CHF/MJ
Generated revenues	0.2 CHF	0.249 CHF	0.129 CHF
Allocation keys for this dataset	**34.5% on disposal service**	**43.1% on heat production**	**22.4% on electricity production**

1 Fees and prices are identical to Tab. 22.8 on page 636.

Alternative allocation factors for the incineration of biowaste, based on the approach presented in (ERZ 2006) are shown in the appendix "Alternative Data for Future Municipal Waste Incinerator".

Tab. 22.13 Unit process raw data of 'biowaste, to municipal incineration, future'

Explanation	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	biowaste, to municipal incineration, future	disposal, biowaste, 60% H2O, to municipal incineration, future, alloc. price	heat, biowaste, at waste incineration plant, future, allocation price	electricity, biowaste, at waste incineration plant, future, alloc. price	biogenic carbon content in elementary flow	biogenic carbon flow
	Location						CH	CH	CH	CH		
	InfrastructureProcess						0	0	0	0		
	Unit						kg	kg	MJ	kWh	kg/kg	kg/f.u.
air, high population density	Carbon monoxide, biogenic	-	air	high population density		kg	0.0002229	34.5	43.1	22.4	42.9%	9.55286E-05
	Carbon monoxide, fossil	-	air	high population density		kg	0	34.5	43.1	22.4		
	Carbon dioxide, biogenic	-	air	high population density		kg	0.588560537	100.0	0.0	0.0	27.3%	0.16051651
	Carbon dioxide, fossil	-	air	high population density		kg	0	34.5	43.1	22.4		
	Methane, biogenic	-	air	high population density		kg	6.38208E-06	34.5	43.1	22.4	75.0%	4.78656E-06
	Methane, fossil	-	air	high population density		kg	0	34.5	43.1	22.4		
	Sulfur dioxide	-	air	high population density		kg	6.38716E-06	34.5	43.1	22.4		
	Nitrogen oxides	-	air	high population density		kg	0.000127265	34.5	43.1	22.4		
	Ammonia	-	air	high population density		kg	3.16944E-06	34.5	43.1	22.4		
	Dinitrogen monoxide	-	air	high population density		kg	1.68912E-05	34.5	43.1	22.4		
	Cyanide	-	air	high population density		kg	3.6E-06	34.5	43.1	22.4		
	Phosphorus	-	air	high population density		kg	1.13E-06	34.5	43.1	22.4		
	Boron	-	air	high population density		kg	1.2288E-06	34.5	43.1	22.4		
	Hydrogen chloride	-	air	high population density		kg	4.44118E-08	34.5	43.1	22.4		
	Bromine	-	air	high population density		kg	1.8E-08	34.5	43.1	22.4		
	Hydrogen fluoride	-	air	high population density		kg	1.05263E-07	34.5	43.1	22.4		
	Iodine	-	air	high population density		kg	5.9391E-13	34.5	43.1	22.4		
	Silver	-	air	high population density		kg	0	34.5	43.1	22.4		
	Arsenic	-	air	high population density		kg	2.04E-14	34.5	43.1	22.4		
	Barium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Cadmium	-	air	high population density		kg	7.59936E-12	34.5	43.1	22.4		
	Cobalt	-	air	high population density		kg	1.5875E-13	34.5	43.1	22.4		
	Chromium	-	air	high population density		kg	5.91527E-13	34.5	43.1	22.4		
	Copper	-	air	high population density		kg	1.32872E-10	34.5	43.1	22.4		
	Mercury	-	air	high population density		kg	2.41761E-15	34.5	43.1	22.4		
	Manganese	-	air	high population density		kg	2.34135E-14	34.5	43.1	22.4		
	Molybdenum	-	air	high population density		kg	7.99999E-10	34.5	43.1	22.4		
	Nickel	-	air	high population density		kg	2.3392E-13	34.5	43.1	22.4		
	Lead	-	air	high population density		kg	6.88925E-10	34.5	43.1	22.4		
	Antimony	-	air	high population density		kg	0	34.5	43.1	22.4		
	Selenium	-	air	high population density		kg	2.51332E-15	34.5	43.1	22.4		
	Tin	-	air	high population density		kg	1.06069E-08	34.5	43.1	22.4		
	Vanadium	-	air	high population density		kg	2.99853E-10	34.5	43.1	22.4		
	Zinc	-	air	high population density		kg	9.5144E-10	34.5	43.1	22.4		
	Beryllium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Scandium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Strontium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Titanium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Thallium	-	air	high population density		kg	0	34.5	43.1	22.4		
	Tungsten	-	air	high population density		kg	0	34.5	43.1	22.4		
	Silicon	-	air	high population density		kg	9.30761E-05	34.5	43.1	22.4		
	Iron	-	air	high population density		kg	2.00308E-08	34.5	43.1	22.4		
	Calcium	-	air	high population density		kg	3.63411E-05	34.5	43.1	22.4		
	Aluminum	-	air	high population density		kg	1.56142E-05	34.5	43.1	22.4		
	Potassium	-	air	high population density		kg	1.05521E-05	34.5	43.1	22.4		
	Magnesium	-	air	high population density		kg	3.88314E-06	34.5	43.1	22.4		
	Sodium	-	air	high population density		kg	1.4113E-05	34.5	43.1	22.4		
water, river	BOD5, Biological Oxygen Demand	-	water	river		kg	6.07738E-06	34.5	43.1	22.4		
	COD, Chemical Oxygen Demand	-	water	river		kg	1.08543E-05	34.5	43.1	22.4		
	TOC, Total Organic Carbon	-	water	river		kg	4.45203E-06	34.5	43.1	22.4	100.0%	4.45203E-06
	DOC, Dissolved Organic Carbon	-	water	river		kg	4.45203E-06	34.5	43.1	22.4		
	Sulfate	-	water	river		kg	0.00072797	34.5	43.1	22.4		
	Nitrate	-	water	river		kg	5.11647E-05	34.5	43.1	22.4		
	Phosphate	-	water	river		kg	2.20936E-07	34.5	43.1	22.4		
	Boron	-	water	river		kg	1.60153E-06	34.5	43.1	22.4		
	Chloride	-	water	river		kg	0.003905573	34.5	43.1	22.4		
	Bromine	-	water	river		kg	4.94481E-06	34.5	43.1	22.4		
	Fluoride	-	water	river		kg	1.5374E-05	34.5	43.1	22.4		
	Iodide	-	water	river		kg	5.49994E-08	34.5	43.1	22.4		
	Silver, ion	-	water	river		kg	0	34.5	43.1	22.4		
	Arsenic, ion	-	water	river		kg	9.01654E-07	34.5	43.1	22.4		
	Barium	-	water	river		kg	0	34.5	43.1	22.4		
	Cadmium, ion	-	water	river		kg	6.25853E-11	34.5	43.1	22.4		
	Cobalt	-	water	river		kg	8.55336E-10	34.5	43.1	22.4		
	Chromium VI	-	water	river		kg	2.6066E-07	34.5	43.1	22.4		
	Copper, ion	-	water	river		kg	7.30928E-10	34.5	43.1	22.4		
	Mercury	-	water	river		kg	7.48568E-10	34.5	43.1	22.4		
	Manganese	-	water	river		kg	2.40573E-10	34.5	43.1	22.4		
	Molybdenum	-	water	river		kg	6.83175E-08	34.5	43.1	22.4		
	Nickel, ion	-	water	river		kg	3.39948E-09	34.5	43.1	22.4		
	Lead	-	water	river		kg	5.17E-10	34.5	43.1	22.4		
	Antimony	-	water	river		kg	0	34.5	43.1	22.4		
	Selenium	-	water	river		kg	1.62774E-07	34.5	43.1	22.4		
	Tin, ion	-	water	river		kg	2.9667E-10	34.5	43.1	22.4		
	Vanadium, ion	-	water	river		kg	2.02326E-09	34.5	43.1	22.4		
	Zinc, ion	-	water	river		kg	1.07076E-08	34.5	43.1	22.4		
	Beryllium	-	water	river		kg	0	34.5	43.1	22.4		
	Scandium	-	water	river		kg	0	34.5	43.1	22.4		
	Strontium	-	water	river		kg	0	34.5	43.1	22.4		
	Titanium, ion	-	water	river		kg	0	34.5	43.1	22.4		
	Thallium	-	water	river		kg	0	34.5	43.1	22.4		
	Tungsten	-	water	river		kg	0	34.5	43.1	22.4		
	Silicon	-	water	river		kg	8.47198E-06	34.5	43.1	22.4		
	Iron, ion	-	water	river		kg	2.05326E-07	34.5	43.1	22.4		
	Calcium, ion	-	water	river		kg	8.24095E-05	34.5	43.1	22.4		
	Aluminum	-	water	river		kg	8.31683E-07	34.5	43.1	22.4		
	Potassium, ion	-	water	river		kg	0.000606918	34.5	43.1	22.4		
	Magnesium	-	water	river		kg	9.87208E-06	34.5	43.1	22.4		
	Sodium, ion	-	water	river		kg	0.000324292	34.5	43.1	22.4		
	Chromium, ion	-	water	river		kg	2.54969E-08	34.5	43.1	22.4		
water, ground-, long-term	BOD5, Biological Oxygen Demand	-	water	ground-, long-term		kg	0.00131088	34.5	43.1	22.4		
	COD, Chemical Oxygen Demand	-	water	ground-, long-term		kg	0.004007609	34.5	43.1	22.4		
	TOC, Total Organic Carbon	-	water	ground-, long-term		kg	0.001585821	34.5	43.1	22.4	100.0%	0.001585821
	DOC, Dissolved Organic Carbon	-	water	ground-, long-term		kg	0.001585821	34.5	43.1	22.4		
	Sulfate	-	water	ground-, long-term		kg	0.003760244	34.5	43.1	22.4		
	Nitrate	-	water	ground-, long-term		kg	0.000143692	34.5	43.1	22.4		
	Phosphate	-	water	ground-, long-term		kg	0.00013234	34.5	43.1	22.4		
	Boron	-	water	ground-, long-term		kg	6.74927E-06	34.5	43.1	22.4		
	Chloride	-	water	ground-, long-term		kg	9.43813E-05	34.5	43.1	22.4		
	Bromine	-	water	ground-, long-term		kg	1.04919E-06	34.5	43.1	22.4		
	Fluoride	-	water	ground-, long-term		kg	0.000178405	34.5	43.1	22.4		
	Iodide	-	water	ground-, long-term		kg	4.60038E-16	34.5	43.1	22.4		
	Silver, ion	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Arsenic, ion	-	water	ground-, long-term		kg	1.09834E-06	34.5	43.1	22.4		
	Barium	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Cadmium, ion	-	water	ground-, long-term		kg	1.38469E-09	34.5	43.1	22.4		
	Cobalt	-	water	ground-, long-term		kg	4.37763E-06	34.5	43.1	22.4		
	Chromium VI	-	water	ground-, long-term		kg	8.4688E-07	34.5	43.1	22.4		
	Copper, ion	-	water	ground-, long-term		kg	1.455E-05	34.5	43.1	22.4		
	Mercury	-	water	ground-, long-term		kg	3.64202E-09	34.5	43.1	22.4		
	Manganese	-	water	ground-, long-term		kg	3.70278E-06	34.5	43.1	22.4		
	Molybdenum	-	water	ground-, long-term		kg	3.30877E-07	34.5	43.1	22.4		
	Nickel, ion	-	water	ground-, long-term		kg	5.07457E-06	34.5	43.1	22.4		
	Lead	-	water	ground-, long-term		kg	1.32234E-06	34.5	43.1	22.4		
	Antimony	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Selenium	-	water	ground-, long-term		kg	3.36022E-07	34.5	43.1	22.4		
	Tin, ion	-	water	ground-, long-term		kg	4.01949E-06	34.5	43.1	22.4		
	Vanadium, ion	-	water	ground-, long-term		kg	5.14316E-07	34.5	43.1	22.4		
	Zinc, ion	-	water	ground-, long-term		kg	9.0294E-07	34.5	43.1	22.4		
	Beryllium	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Scandium	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Strontium	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Titanium, ion	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Thallium	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Tungsten	-	water	ground-, long-term		kg	0	34.5	43.1	22.4		
	Silicon	-	water	ground-, long-term		kg	0.003471678	34.5	43.1	22.4		
	Iron, ion	-	water	ground-, long-term		kg	0.000281043	34.5	43.1	22.4		
	Calcium, ion	-	water	ground-, long-term		kg	0.018970982	34.5	43.1	22.4		
	Aluminum	-	water	ground-, long-term		kg	0.00739674	34.5	43.1	22.4		
	Potassium, ion	-	water	ground-, long-term		kg	0.002882528	34.5	43.1	22.4		
	Magnesium	-	water	ground-, long-term		kg	0.002603213	34.5	43.1	22.4		
	Sodium, ion	-	water	ground-, long-term		kg	0.001161594	34.5	43.1	22.4		
technosphere	municipal waste incineration plant	CH	waste management	municipal incineration	1	unit	2.5E-10	34.5	43.1	22.4		
	process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	0	kg	1	34.5	43.1	22.4		
	slag compartment	CH	waste management	municipal incineration	1	unit	2.37745E-10	34.5	43.1	22.4		
	process-specific burdens, slag compartment	CH	waste management	municipal incineration	0	kg	0.133731793	34.5	43.1	22.4		
	residual material landfill facility	CH	waste management	residual material landfill	1	unit	3.92362E-11	34.5	43.1	22.4		
	process-specific burdens, residual material landfill	CH	waste management	residual material landfill	0	kg	0.018833388	34.5	43.1	22.4		
air, high population density	Heat, waste	-	air	high population density		MJ	5.294354571	34.5	43.1	22.4		
water, river	Heat, waste	-	water	river		MJ	1.393374217	34.5	43.1	22.4		
technosphere	electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	kWh	0	34.5	43.1	22.4		
	heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	MJ	0	34.5	43.1	22.4		
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	0	kg	0.004484384	34.5	43.1	22.4		
	quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.000697472	34.5	43.1	22.4		
	hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	0	kg	7.72526E-06	34.5	43.1	22.4		
	iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	7.84536E-06	34.5	43.1	22.4		
	chemicals organic, at plant	GLO	chemicals	organics	0	kg	7.04428E-07	34.5	43.1	22.4		
	chemicals inorganic, at plant	GLO	chemicals	inorganics	0	kg	1.28754E-05	34.5	43.1	22.4		
	cement, unspecified, at plant	CH	construction materials	binder	0	kg	0.007533355	34.5	43.1	22.4		
	disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	0	kg	0.018833388	34.5	43.1	22.4		
	transport, freight, rail	RER	transport systems	train	0	tkm	0.010308482	34.5	43.1	22.4		
	transport, lorry 28t	CH	transport systems	road	0	tkm	0.007285452	34.5	43.1	22.4		
	ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	0.0002018	34.5	43.1	22.4		
	natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	0	MJ	0.019679987	34.5	43.1	22.4		
	titanium dioxide, production mix, at plant	RER	chemicals	inorganics	0	kg	5.77649E-06	34.5	43.1	22.4		
	chromium oxide, flakes, at plant	RER	chemicals	inorganics	0	kg	1.17888E-07	34.5	43.1	22.4		
	transport, municipal waste collection, lorry 21t	CH	waste management	others	0	tkm	0.01	34.5	43.1	22.4		
allocated products	disposal, biowaste, 60% H2O, to municipal incineration, future, alloc. pric	CH	waste management	municipal incineration	0	kg	1	100.0	0.0	0.0	-16.2%	-0.162399893
	heat, biowaste, at waste incineration plant, future, allocation price	CH	waste management	municipal incineration	0	MJ	2.7721	0.0	100.0	0.0	0.0%	0
	electricity, biowaste, at waste incineration plant, future, alloc. price	CH	waste management	municipal incineration	0	kWh	0.1368	0.0	0.0	100.0	0.0%	0
Carbon Balance	Biogenic Carbon input					kg	0.000	0.000	0.000	0.000	totals	0.000
	Biogenic Carbon output in products					kg	-0.162	-0.162	0.000	0.000		-0.162
	Biogenic Carbon emissions, except CO2					kg	0.002	0.001	0.001	0.000		0.002
	Biogenic CO2 emissions					kg	0.161	0.161	0.000	0.000		0.161
	Carbon balance (inputs - outputs)						0.000	-0.001	0.001	0.000		0.000

22.8 Life cycle inventory of digested sewage sludge incineration in municipal waste incinerator, current

In this life cycle inventory the incineration of digested sewage sludge in a current municipal waste incinerator is presented. The composition of digested sewage sludge, i.e. after biogas production in the fermenter, is adopted from (Doka 2003), but the conversion rate of organic matter to biogas was altered to 45%, based on data in chapter 4 (see Tab. 22.2 on page 630).

The system boundaries comprise dewatering of the sludge from a water content of 95% to 73%, disposal of the produced dewatering liquid, transport of the dewatered sludge to the incinerator, incineration expenditures, and landfilling of solid residues.

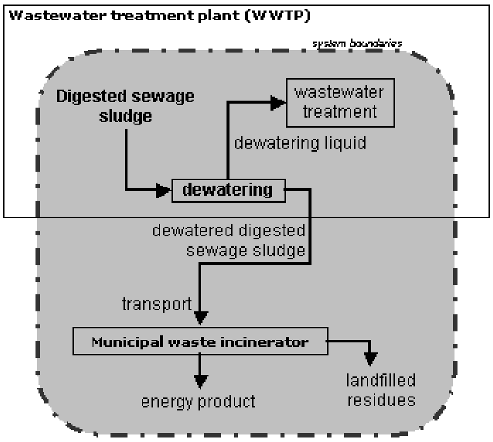

Fig. 22.5 System boundaries of digested sludge incineration in municipal waste incinerator

It will be shown below, that no net energy can be produced from this process. Thus the dataset represents an unit process for disposal. The functional unit of the dataset 'disposal, digester sludge, to municipal incineration' is 1 kilogram of wet digested sewage sludge with a water content of 95%.

Dewatering process

Prior to incineration, the sludge is dewatered from 95% to 73% water content. The dewatering process is described qualitatively in chapter 22.5.2 'Sludge dewatering process description' on page 632. Dewatering is assumed to occur within the wastewater treatment plant. Dewatering is included in this inventory to have comparable system boundaries to biogas from sewage sludge digestion (see chapter 4).

An average energy demand of several dewatering technologies of 0.0015 kWh electricity per kilogram wet sludge input is adopted from (Böhler et al. 2003). Most technologies also require the addition of flocculation agents to aggregate sludge particles. From (Böhler et al. 2003) the input of flocculation agents (quick lime, ferric chloride, polyelectrolyte) is adopted, see Tab. 22.14.

Tab. 22.14 Specific input of flocculation agents for dewatering process

Flocculation agent	**Specific input** (Böhler et al. 2003)		**This study** kg agent per kg wet sludge input
CaO	kg per m^3 input	7	**0.00233**
$FeCl_3$	kg per m^3 input	3.75	**0.00125**
Polyelectrolyte / polymer	kg per ton dry matter input	6.3	**0.0002625**

Approximately 820 grams of dewatering liquid are removed from the wet sludge by dewatering. This liquid is rich in ammonia, and is subsequently recycled into the wastewater treatment plant. The inventory of the disposal of dewatering liquid is calculated by application of the existing calculation tool for municipal wastewater treatment provided and described in (Doka 2003)[60]. The composition of dewatering liquid is shown in Tab. 22.15. The removal of these pollutants is heeded in the composition of the remaining dewatered sludge.

Tab. 22.15 Composition of dewatering liquid

Dewatering liquid composition		Siegrist 2006	Moser 2006	Fasel 2006	**This study**
Ammonia nitrogen (NH_4-N)	g/m^3	600 – 1000	500 – 800	984	**776.8**
Total organic carbon (TOC)	g/m^3			681	**681**
Soluble phosphorus (P_{sol})	g/m^3			16	**16**

Infrastructure for dewatering process

Data for the infrastructure of the dewatering process is approximated with infrastructure of a pump station used in drinking water supply (Althaus et al. 2004:803). A total uptake of 100 million tons of sludge input over the lifetime of the facility is assumed, resulting in a requirement of 10^{-11} units per kilogram wet sludge.

Transport to incinerator

Over 900 WWT plants exist in Switzerland, but only 28 waste incinerators. It is assumed that transport distances are on average 25 km. Transport per lorry 28t is assumed.

Municipal waste incinerator

The incineration process is described qualitatively in chapter 22.5.3 'Municipal incineration process description' on page 632. Per functional unit of 1 kg wet digested sludge, approximately 180 grams of dewatered digested sludge are incinerated. The direct emissions from sludge incineration are calculated according to the calculated elemental composition of digested sludge after dewatering (waste-specific emissions). Exchanges are calculated with the existing ecoinvent calculation tool for municipal waste incineration described and provided in (Doka 2003). The incinerator technology represents the Swiss average for municipal incinerators in 2000.

Energy production

At a water content of 73%, the dewatered digested sludge has a lower heating value of 2.4 MJ/kg (Michel 1938). Per functional unit (f.u.) only 179 grams dewatered sludge, or 0.43 MJ enter the MSWI. The incinerator converts that energy with a gross heat generation efficiency of 25.6% and a gross electricity generation efficiency of 13%, which represents the average efficiencies of Swiss MSWI in 2000. The internal energy consumption of the waste incinerator is 0.839 MJ heat and 0.144 kWh (0.518 MJ) electricity per kilogram incinerated waste (BUWAL 2001b), and proportionally less per functional unit. As shown in Tab. 22.16 in this average situation *no net energy* can be generated from dewatered digested sludge in an municipal waste incinerator.

This result is based on generic Swiss data. It is possible that incineration of dewatered digested sludge can generate net energy, especially if water content of dewatered sludge is below 70%, or if internal energy consumption of the plant is lower. However, based on the Swiss average data applied here, no net energy gain can be expected.

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[60] In that tool, the full disposal chain of wastewater treatment is included by default (sewer transport, overload discharge, three-stage treatment in WWTP, sludge digestion and disposal of sludge). In order to assess the burdens created by internal treatment of dewatering liquid from digested sludge, only the burdens from 'three-stage treatment in WWTP' and 'sludge digestion' are heeded here, since the downstream fate of digested sludge is already being assessed. Overload discharge is set to zero.

Tab. 22.16 Energy generated from dewatered digested sludge in municipal waste incinerator

Dewatered digested sludge lower heating value	MJ/kg	2.4	
Energy input per f.u.	MJ/f.u.	0.43	
		Heat	Electricity
Gross energy efficiency	%	25.57%	13%
Generated gross energy	MJ/f.u.	0.111	0.056
Internal consumption	MJ/kg	0.839	0.518
per f.u.	MJ/f.u.	0.150	0.093
Generated net energy	MJ/f.u.	-0.039	-0.036

Allocation

As noted above, incineration of dewatered digested sludge in a Swiss municipal waste incinerator generates no net energy. Thus, this process provides only *one* useful service: disposal of digested sludge. No allocation is necessary. The dataset is created as a simple unit process inventory.

Data quality considerations

The general procedures to calculate uncertainty information of the datasets of this chapter are described in 22.5.5 'General Data Quality Considerations' on page 634. Additional information on the MO-process 'digester sludge, to municipal incineration', not already heeded in the calculation tools of (Doka 2003) is displayed below.

Tab. 22.17 Uncertainty estimates for exchanges of the sludge dewatering process

Exchanges	**Uncertainty factors** SDG^2 of a lognormal distribution	**Pedigree codes**	**Comment**
Pollutants in dewatering liquid	1.58	(1,1,3,1,3,1)	basic uncertainty of 1.5; data from two sources
Infrastructure for dewatering facility	3.73	(1,3,3,1,5,5)	basic uncertainty of 3; approximation with water pump station
energy demand for dewatering process	1.05	(1,2,1,1,1,1)	basic uncertainty of 1.05; Literature values
flocculation agents for dewatering process	1.07	(1,3,1,1,1,1)	basic uncertainty of 1.05; Literature values

Tab. 22.18 Unit process raw data of 'disposal, digester sludge, to municipal incineration'

Explanation	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	disposal, digester sludge, to incineration	biogenic carbon content in elementary flow	biogenic carbon flow
	Location InfrastructureProcess Unit						CH 0 kg	kg/kg	kg/f.u.
water, river	Ammonium, ion	-	water	river	0	kg	0.000267775		
	Nitrogen	-	water	river	0	kg	1.83809E-05		
air, high population density	NMVOC, non-methane volatile organic compounds, unspecified origin	-	air	high population density	0	kg	1.92704E-08		
	Carbon monoxide, biogenic	-	air	high population density	0	kg	4.12589E-05	42.9%	1.76824E-05
	Carbon dioxide, biogenic	-	air	high population density	0	kg	0.061599457	27.3%	0.01679992
	Methane, biogenic	-	air	high population density	0	kg	5.38385E-06	75.0%	4.03789E-06
	Sulfur dioxide	-	air	high population density	0	kg	4.71387E-06		
	Nitrogen oxides	-	air	high population density	0	kg	4.39628E-05		
	Ammonia	-	air	high population density	0	kg	2.04032E-06		
	Dinitrogen monoxide	-	air	high population density	0	kg	6.81865E-06		
	Cyanide	-	air	high population density	0	kg	9.33358E-07		
	Phosphorus	-	air	high population density	0	kg	1.54633E-06		
	Arsenic	-	air	high population density	0	kg	1.42438E-15		
	Cadmium	-	air	high population density	0	kg	5.47224E-12		
	Cobalt	-	air	high population density	0	kg	1.81881E-14		
	Chromium	-	air	high population density	0	kg	3.20274E-13		
	Copper	-	air	high population density	0	kg	1.47185E-10		
	Mercury	-	air	high population density	0	kg	3.43207E-15		
	Manganese	-	air	high population density	0	kg	1.0219E-13		
	Molybdenum	-	air	high population density	0	kg	6.78073E-10		
	Nickel	-	air	high population density	0	kg	8.0478E-14		
	Lead	-	air	high population density	0	kg	2.05043E-10		
	Tin	-	air	high population density	0	kg	1.88627E-09		
	Zinc	-	air	high population density	0	kg	8.87432E-10		
	Silicon	-	air	high population density	0	kg	4.91914E-06		
	Iron	-	air	high population density	0	kg	3.18542E-07		
	Calcium	-	air	high population density	0	kg	5.9771E-06		
	Aluminum	-	air	high population density	0	kg	1.65466E-06		
	Magnesium	-	air	high population density	0	kg	5.54299E-07		
water, river	BOD5, Biological Oxygen Demand	-	water	river	0	kg	6.9471E-05		
	COD, Chemical Oxygen Demand	-	water	river	0	kg	0.000233474		
	TOC, Total Organic Carbon	-	water	river	0	kg	5.45766E-05	100.0%	5.45766E-05
	DOC, Dissolved Organic Carbon	-	water	river	0	kg	5.45766E-05		
	Sulfate	-	water	river	0	kg	0.000591885		
	Nitrate	-	water	river	0	kg	0.00122858		
	Phosphate	-	water	river	0	kg	1.44871E-05		
	Chloride	-	water	river	0	kg	5.69556E-05		
	Arsenic, ion	-	water	river	0	kg	6.2956E-08		
	Cadmium, ion	-	water	river	0	kg	4.50673E-11		
	Cobalt	-	water	river	0	kg	9.79968E-11		
	Chromium VI	-	water	river	0	kg	1.41131E-07		
	Copper, ion	-	water	river	0	kg	8.09661E-10		
	Mercury	-	water	river	0	kg	1.06267E-09		
	Manganese	-	water	river	0	kg	1.05E-09		
	Molybdenum	-	water	river	0	kg	5.79053E-08		
	Nickel, ion	-	water	river	0	kg	1.16956E-09		
	Lead	-	water	river	0	kg	1.53873E-10		
	Tin, ion	-	water	river	0	kg	5.2758E-11		
	Zinc, ion	-	water	river	0	kg	9.98725E-09		
	Silicon	-	water	river	0	kg	4.4775E-07		
	Iron, ion	-	water	river	0	kg	3.26523E-06		
	Calcium, ion	-	water	river	0	kg	1.35541E-05		
	Aluminum	-	water	river	0	kg	8.81348E-08		
	Magnesium	-	water	river	0	kg	1.40919E-06		
	Chromium, ion	-	water	river	0	kg	1.38049E-08		
water, ground-, long-term	BOD5, Biological Oxygen Demand	-	water	ground-, long-term	0	kg	0.000134519		
	COD, Chemical Oxygen Demand	-	water	ground-, long-term	0	kg	0.000411249		
	TOC, Total Organic Carbon	-	water	ground-, long-term	0	kg	0.000162732	100.0%	0.000162733
	DOC, Dissolved Organic Carbon	-	water	ground-, long-term	0	kg	0.000162732		
	Sulfate	-	water	ground-, long-term	0	kg	0.002775151		
	Nitrate	-	water	ground-, long-term	0	kg	3.72546E-05		
	Phosphate	-	water	ground-, long-term	0	kg	0.000181099		
	Arsenic, ion	-	water	ground-, long-term	0	kg	7.66895E-08		
	Cadmium, ion	-	water	ground-, long-term	0	kg	9.97103E-10		
	Cobalt	-	water	ground-, long-term	0	kg	5.0155E-07		
	Chromium VI	-	water	ground-, long-term	0	kg	4.58531E-07		
	Copper, ion	-	water	ground-, long-term	0	kg	1.61173E-05		
	Mercury	-	water	ground-, long-term	0	kg	5.17025E-09		
	Manganese	-	water	ground-, long-term	0	kg	1.61611E-05		
	Molybdenum	-	water	ground-, long-term	0	kg	2.80449E-07		
	Nickel, ion	-	water	ground-, long-term	0	kg	1.74586E-06		
	Lead	-	water	ground-, long-term	0	kg	3.93564E-07		
	Tin, ion	-	water	ground-, long-term	0	kg	7.14802E-07		
	Zinc, ion	-	water	ground-, long-term	0	kg	8.42195E-07		
	Silicon	-	water	ground-, long-term	0	kg	0.000183481		
	Iron, ion	-	water	ground-, long-term	0	kg	0.004469324		
	Calcium, ion	-	water	ground-, long-term	0	kg	0.003120201		
	Aluminum	-	water	ground-, long-term	0	kg	0.000783845		
	Magnesium	-	water	ground-, long-term	0	kg	0.000371596		
technosphere	municipal waste incineration plant	CH	waste management	municipal incineration	1	unit	4.4827E-11		
	process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	0	kg	0.179308045		
	slag compartment	CH	waste management	municipal incineration	1	unit	4.91773E-11		
	process-specific burdens, slag compartment	CH	waste management	municipal incineration	0	kg	0.027662232		
	residual material landfill facility	CH	waste management	residual material landfill	1	unit	9.06574E-12		
	process-specific burdens, residual material landfill	CH	waste management	residual material landfill	0	kg	0.004351556		
air, high population density	Heat, waste	-	air	high population density	0	MJ	0.69038728		
water, river	Heat, waste	-	water	river	0	MJ	0.198810477		
technosphere	electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	kWh	0.010109672		
	heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	MJ	0.039404684		
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	0	kg	0.000411102		
	quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.002334494		
	hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	0	kg	4.79687E-07		
	iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	0.001343359		
	chemicals organic, at plant	GLO	chemicals	organics	0	kg	0.000263116		
	chemicals inorganic, at plant	GLO	chemicals	inorganics	0	kg	7.99478E-07		
	cement, unspecified, at plant	CH	construction materials	binder	0	kg	0.00174062		
	disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	0	kg	0.004351549		
	transport, freight, rail	RER	transport systems	train	0	tkm	0.001235809		
	transport, lorry 28t	CH	transport systems	road	0	tkm	0.005948622		
	ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	5.232E-05		
	natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	0	MJ	0.005102362		
	titanium dioxide, production mix, at plant	RER	chemicals	inorganics	0	kg	1.49765E-06		
	chromium oxide, flakes, at plant	RER	chemicals	inorganics	0	kg	3.05643E-08		
	electricity, low voltage, at grid	CH	electricity	supply mix	0	kWh	0.005429102		
	iron sulphate, at plant	RER	metals	extraction	0	kg	6.35336E-05		
	aluminium sulphate, powder, at plant	RER	chemicals	inorganics	0	kg	1.7171E-05		
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05		
	disposal, paper, 11.2% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05		
	wastewater treatment plant, class 3	CH	waste management	wastewater treatment	1	unit	4.66825E-12		
technosphere	pump station	CH	water supply	production	1	unit	1E-11		
products	disposal, digester sludge, to municipal incineration	CH	waste management	municipal incineration	0	kg	1	-1.7%	-0.017224003
Carbon Balance	Biogenic Carbon input					kg	0.000	totals	0.000
	Biogenic Carbon output in products					kg	-0.017		-0.017
	Biogenic Carbon emissions, except CO2					kg	0.000		0.000
	Biogenic CO2 emissions					kg	0.017		0.017
	Carbon balance (inputs - outputs)						0.000		0.000

22.9 Life cycle inventory of digested sewage sludge incineration in municipal waste incinerator, future

In this life cycle inventory the incineration of digested sewage sludge in a *future* municipal waste incinerator is presented. The waste composition, the process, system boundary and functional units are in large parts identical to incineration of digested sewage in current municipal waste incinerators, presented in chapter 22.8 'Life cycle inventory of digested sewage sludge incineration in municipal waste incinerator, current' above.

The system boundaries comprise dewatering of the sludge from a water content of 95% to 73%, disposal of the produced dewatering liquid, transport of the dewatered sludge to the incinerator, incineration expenditures, and landfilling of solid residues. For the energy products the system cuts off after the incinerator, i.e. distribution and losses of energy by electricity grid or district heating network are not heeded.

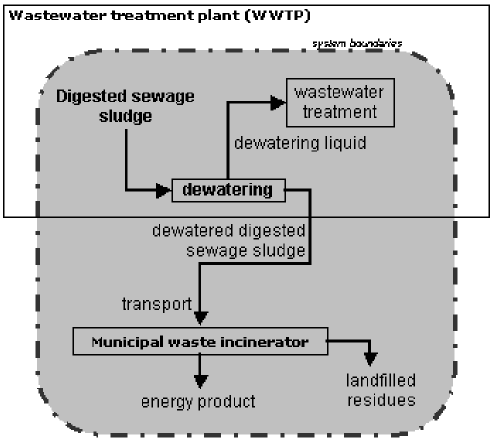

Fig. 22.6 System boundaries of digested sludge incineration in future municipal waste incinerator

The functional unit of the multi-output process 'digester sludge, to municipal incineration, future' is 1 kilogram of wet digested sewage sludge with a water content of 95%. The generated unit process inventories are shown below.

Tab. 22.19 Datasets derived from the multi-output process 'digester sludge, to municipal incineration, future'

Service function	Unit process dataset	Functional unit
disposal	disposal, digester sludge, to incineration, future, allocation price	1 kg wet sludge
net useful heat	heat, digester sludge, at incineration plant, future, allocation price	1 MJ
net electricity	electricity, digester sludge, at incineration plant, future, alloc. price	1 kWh

Dewatering and transport

Prior to incineration the sludge is dewatered from 95% to 73% water content. The process and the burdens are identical to the ones documented in chapter 22.8 'Life cycle inventory of digested sewage sludge incineration in municipal waste incinerator, current' on page 643.

Incineration

The dewatered sludge is incinerated in a municipal waste incinerator. The incineration process is described qualitatively in chapter 22.5.3 'Municipal incineration process description' on page 632. The inventory of direct burdens is calculated according to the defined elemental sludge composition (waste-specific emissions) using the existing ecoinvent calculation tool for municipal waste incineration provided in (Doka 2003). The gross energy production efficiencies and internal energy consumption in the future incinerator are identical to the ones used in chapter 22.7 'Life cycle inventory of biowaste incineration in municipal waste incinerator, future' on page 638.

Energy production

At a water content of 73%, the dewatered digested sludge has a lower heating value of 2.4 MJ/kg (Michel 1938). Per functional unit only 0.179 grams dewatered sludge, or 0.43 MJ enter the MSWI. The future incinerator has a gross heat generation efficiency of 56.3% and a gross electric efficiency of 16.7%. The internal energy consumption of the future waste incinerator is 0.99 MJ heat and 0.36 MJ electricity per kilogram incinerated waste[61], and proportionally less per f.u.. As shown in Tab. 22.21 the future MSWI generates positive net energy from dewatered digested sludge.

Tab. 22.20 Energy generated from dewatered digested sludge in *future* municipal waste incinerator

Dewatered digested sludge lower heating value	MJ/kg	2.4	
Energy input per f.u.	MJ/f.u.	0.43	
		Heat	Electricity
Gross energy efficiency	%	56.25	16.7%
Generated gross energy	MJ/f.u.	0.244	0.072
Internal consumption	MJ/kg	0.099	0.360
per f.u.	MJ/f.u.	0.018	0.065
Generated net energy [1]	MJ/f.u.	0.2264	0.008 (0.0022 kWh/f.u.)

1 Net energy production is gross production *minus* internal consumption

Allocation

The inventoried exchanges are allocated according to the outline given in chapter 22.5.4 'General Allocation Choices' on page 633. For the allocation with an economical key current disposal fees and energy prices are used. In sludge disposal trade the disposal price is usually given in relation to the dry matter content of the sludge. This is converted here to a price for wet sludge with 95% water content. No extrapolation to future price levels is attempted. The disposal fee per functional unit is given in Tab. 22.21. The revenues for heat and electricity production in Swiss municipal incinerators are taken from (Dettli et al. 2004:19ff).

Tab. 22.21 Disposal fees for sewage sludge in municipal incinerator

		Source
Disposal fee per metric ton of sludge dry matter (DM)	802 CHF / t DM	BUWAL 2004a
Disposal fee per kilogram wet sludge with 95% water content	0.04 CHF / kg_{wet}	calculation
This study	**0.04 CHF / kg_{wet}**	

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[61] Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), April 3, 2006.

Tab. 22.22 Revenues generated from one kilogram of digested sewage sludge in future municipal waste incinerator

per f.u.	*Disposal service*	*Sold heat*	*Sold electricity*
Valued amounts	1 kg	0.2264 MJ	0.00793 MJ
Fees and prices	0.0401 CHF/kg	0.09 CHF/MJ	0.2628 CHF/MJ
Generated revenues	0.0401 CHF	0.0204 CHF	0.00208 CHF
Allocation keys	**64.1%**	**32.6%**	**3.3%**
for this dataset	**on disposal service**	**on heat production**	**on electricity production**

1 Energy prices are identical to Tab. 22.8 on page 636.

Tab. 22.23 Unit process raw data of 'digester sludge, to municipal incineration, future'

Explanation	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	digester sludge, to municipal incineration, future	disposal, digester sludge, to incineration, future, allocation price	heat, digester sludge, at incineration plant, future, allocation price	electricity, digester sludge, at incineration plant, future, alloc. price	biogenic carbon content in elementary flow	biogenic carbon flow
	Location InfrastructureProcess Unit						CH 0 kg	CH 0 kg	CH 0 MJ	CH 0 kWh	kg/kg	kg/f.u.
water, river	Ammonium, ion	-	water	river	0	kg	0.000267775	64.1	32.6	3.3		
	Nitrogen	-	water	river	0	kg	1.83809E-05	64.1	32.6	3.3		
air, high population density	NMVOC, non-methane volatile organic compounds, unspecified origir	-	air	high population density	0	kg	1.92704E-08	64.1	32.6	3.3		
	Carbon monoxide, biogenic	-	air	high population density	0	kg	4.12588E-05	64.1	32.6	3.3	42.9%	1.76824E-05
	Carbon dioxide, biogenic	-	air	high population density	0	kg	0.061599706	100.0	0.0	0.0	27.3%	0.01679992
	Methane, biogenic	-	air	high population density	0	kg	5.38385E-06	64.1	32.6	3.3	75.0%	4.03789E-06
	Sulfur dioxide	-	air	high population density	0	kg	4.71389E-06	64.1	32.6	3.3		
	Nitrogen oxides	-	air	high population density	0	kg	4.39629E-05	64.1	32.6	3.3		
	Ammonia	-	air	high population density	0	kg	2.04032E-06	64.1	32.6	3.3		
	Dinitrogen monoxide	-	air	high population density	0	kg	6.81867E-06	64.1	32.6	3.3		
	Cyanide	-	air	high population density	0	kg	9.33361E-07	64.1	32.6	3.3		
	Phosphorus	-	air	high population density	0	kg	1.54633E-06	64.1	32.6	3.3		
	Arsenic	-	air	high population density	0	kg	1.42439E-15	64.1	32.6	3.3		
	Cadmium	-	air	high population density	0	kg	5.47226E-12	64.1	32.6	3.3		
	Cobalt	-	air	high population density	0	kg	1.81882E-14	64.1	32.6	3.3		
	Chromium	-	air	high population density	0	kg	3.20275E-13	64.1	32.6	3.3		
	Copper	-	air	high population density	0	kg	1.47185E-10	64.1	32.6	3.3		
	Mercury	-	air	high population density	0	kg	3.43208E-15	64.1	32.6	3.3		
	Manganese	-	air	high population density	0	kg	1.0219E-13	64.1	32.6	3.3		
	Molybdenum	-	air	high population density	0	kg	6.78075E-10	64.1	32.6	3.3		
	Nickel	-	air	high population density	0	kg	8.04782E-14	64.1	32.6	3.3		
	Lead	-	air	high population density	0	kg	2.05044E-10	64.1	32.6	3.3		
	Tin	-	air	high population density	0	kg	1.88628E-09	64.1	32.6	3.3		
	Zinc	-	air	high population density	0	kg	8.87435E-10	64.1	32.6	3.3		
	Silicon	-	air	high population density	0	kg	4.91915E-06	64.1	32.6	3.3		
	Iron	-	air	high population density	0	kg	3.18543E-07	64.1	32.6	3.3		
	Calcium	-	air	high population density	0	kg	5.97711E-06	64.1	32.6	3.3		
	Aluminum	-	air	high population density	0	kg	1.65467E-06	64.1	32.6	3.3		
	Magnesium	-	air	high population density	0	kg	5.54301E-07	64.1	32.6	3.3		
water, river	BOD5, Biological Oxygen Demand	-	water	river	0	kg	6.9471E-05	64.1	32.6	3.3		
	COD, Chemical Oxygen Demand	-	water	river	0	kg	0.000233474	64.1	32.6	3.3		
	TOC, Total Organic Carbon	-	water	river	0	kg	5.45766E-05	64.1	32.6	3.3	100.0%	5.45766E-05
	DOC, Dissolved Organic Carbon	-	water	river	0	kg	5.45766E-05	64.1	32.6	3.3		
	Sulfate	-	water	river	0	kg	0.000591887	64.1	32.6	3.3		
	Nitrate	-	water	river	0	kg	0.001228581	64.1	32.6	3.3		
	Phosphate	-	water	river	0	kg	1.44871E-05	64.1	32.6	3.3		
	Chloride	-	water	river	0	kg	5.69556E-05	64.1	32.6	3.3		
	Arsenic, ion	-	water	river	0	kg	6.29562E-08	64.1	32.6	3.3		
	Cadmium, ion	-	water	river	0	kg	4.50674E-11	64.1	32.6	3.3		
	Cobalt	-	water	river	0	kg	9.79971E-11	64.1	32.6	3.3		
	Chromium VI	-	water	river	0	kg	1.41131E-07	64.1	32.6	3.3		
	Copper, ion	-	water	river	0	kg	8.09663E-10	64.1	32.6	3.3		
	Mercury	-	water	river	0	kg	1.06268E-09	64.1	32.6	3.3		
	Manganese	-	water	river	0	kg	1.05E-09	64.1	32.6	3.3		
	Molybdenum	-	water	river	0	kg	5.79055E-08	64.1	32.6	3.3		
	Nickel, ion	-	water	river	0	kg	1.16956E-09	64.1	32.6	3.3		
	Lead	-	water	river	0	kg	1.53874E-10	64.1	32.6	3.3		
	Tin, ion	-	water	river	0	kg	5.27582E-11	64.1	32.6	3.3		
	Zinc, ion	-	water	river	0	kg	9.98728E-09	64.1	32.6	3.3		
	Silicon	-	water	river	0	kg	4.47751E-07	64.1	32.6	3.3		
	Iron, ion	-	water	river	0	kg	3.26524E-06	64.1	32.6	3.3		
	Calcium, ion	-	water	river	0	kg	1.35541E-05	64.1	32.6	3.3		
	Aluminum	-	water	river	0	kg	8.81351E-08	64.1	32.6	3.3		
	Magnesium	-	water	river	0	kg	1.4092E-06	64.1	32.6	3.3		
	Chromium, ion	-	water	river	0	kg	1.3805E-08	64.1	32.6	3.3		
water, ground-, long-term	BOD5, Biological Oxygen Demand	-	water	ground-, long-term	0	kg	0.000134519	64.1	32.6	3.3		
	COD, Chemical Oxygen Demand	-	water	ground-, long-term	0	kg	0.000411251	64.1	32.6	3.3		
	TOC, Total Organic Carbon	-	water	ground-, long-term	0	kg	0.000162733	64.1	32.6	3.3	100.0%	0.000162733
	DOC, Dissolved Organic Carbon	-	water	ground-, long-term	0	kg	0.000162733	64.1	32.6	3.3		
	Sulfate	-	water	ground-, long-term	0	kg	0.002775158	64.1	32.6	3.3		
	Nitrate	-	water	ground-, long-term	0	kg	3.72547E-05	64.1	32.6	3.3		
	Phosphate	-	water	ground-, long-term	0	kg	0.000181099	64.1	32.6	3.3		
	Arsenic, ion	-	water	ground-, long-term	0	kg	7.66897E-08	64.1	32.6	3.3		
	Cadmium, ion	-	water	ground-, long-term	0	kg	9.97106E-10	64.1	32.6	3.3		
	Cobalt	-	water	ground-, long-term	0	kg	5.01551E-07	64.1	32.6	3.3		
	Chromium VI	-	water	ground-, long-term	0	kg	4.58533E-07	64.1	32.6	3.3		
	Copper, ion	-	water	ground-, long-term	0	kg	1.61173E-05	64.1	32.6	3.3		
	Mercury	-	water	ground-, long-term	0	kg	5.17026E-09	64.1	32.6	3.3		
	Manganese	-	water	ground-, long-term	0	kg	1.61611E-05	64.1	32.6	3.3		
	Molybdenum	-	water	ground-, long-term	0	kg	2.8045E-07	64.1	32.6	3.3		
	Nickel, ion	-	water	ground-, long-term	0	kg	1.74586E-06	64.1	32.6	3.3		
	Lead	-	water	ground-, long-term	0	kg	3.93565E-07	64.1	32.6	3.3		
	Tin, ion	-	water	ground-, long-term	0	kg	7.14804E-07	64.1	32.6	3.3		
	Zinc, ion	-	water	ground-, long-term	0	kg	8.42197E-07	64.1	32.6	3.3		
	Silicon	-	water	ground-, long-term	0	kg	0.000183481	64.1	32.6	3.3		
	Iron, ion	-	water	ground-, long-term	0	kg	0.004469336	64.1	32.6	3.3		
	Calcium, ion	-	water	ground-, long-term	0	kg	0.00312021	64.1	32.6	3.3		
	Aluminum	-	water	ground-, long-term	0	kg	0.000783847	64.1	32.6	3.3		
	Magnesium	-	water	ground-, long-term	0	kg	0.000371597	64.1	32.6	3.3		
technosphere	municipal waste incineration plant	CH	waste management	municipal incineration	1	unit	4.4827E-11	64.1	32.6	3.3		
	process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	0	kg	0.179307883	64.1	32.6	3.3		
	slag compartment	CH	waste management	municipal incineration	1	unit	4.91775E-11	64.1	32.6	3.3		
	process-specific burdens, slag compartment	CH	waste management	municipal incineration	0	kg	0.027662323	64.1	32.6	3.3		
	residual material landfill facility	CH	waste management	residual material landfill	1	unit	9.06577E-12	64.1	32.6	3.3		
	process-specific burdens, residual material landfill	CH	waste management	residual material landfill	0	kg	0.00435157	64.1	32.6	3.3		
air, high population density	Heat, waste	-	air	high population density	0	MJ	0.662223013	64.1	32.6	3.3		
water, river	Heat, waste	-	water	river	0	MJ	0.190795925	64.1	32.6	3.3		
	sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	0	kg	0.000411104	64.1	32.6	3.3		
	quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.002334494	64.1	32.6	3.3		
	hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	0	kg	4.79688E-07	64.1	32.6	3.3		
	iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	0.001343359	64.1	32.6	3.3		
	chemicals organic, at plant	GLO	chemicals	organics	0	kg	0.000263116	64.1	32.6	3.3		
	chemicals inorganic, at plant	GLO	chemicals	inorganics	0	kg	7.99481E-07	64.1	32.6	3.3		
	cement, unspecified, at plant	CH	construction materials	binder	0	kg	0.001740628	64.1	32.6	3.3		
	disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	0	kg	0.00435157	64.1	32.6	3.3		
	transport, freight, rail	RER	transport systems	train	0	tkm	0.001235812	64.1	32.6	3.3		
	transport, lorry 28t	CH	transport systems	road	0	tkm	0.005948623	64.1	32.6	3.3		
	ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	5.23201E-05	64.1	32.6	3.3		
	natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	0	MJ	0.005102373	64.1	32.6	3.3		
	titanium dioxide, production mix, at plant	RER	chemicals	inorganics	0	kg	1.49765E-06	64.1	32.6	3.3		
	chromium oxide, flakes, at plant	RER	chemicals	inorganics	0	kg	3.05644E-08	64.1	32.6	3.3		
	electricity, low voltage, at grid	CH	electricity	supply mix	0	kWh	0.005429104	64.1	32.6	3.3		
	iron sulphate, at plant	RER	metals	extraction	0	kg	6.35336E-05	64.1	32.6	3.3		
	aluminium sulphate, powder, at plant	RER	chemicals	inorganics	0	kg	1.7171E-05	64.1	32.6	3.3		
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05	64.1	32.6	3.3		
	disposal, paper, 11.2% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05	64.1	32.6	3.3		
	wastewater treatment plant, class 3	CH	waste management	wastewater treatment	1	unit	4.66825E-12	64.1	32.6	3.3		
technosphere	pump station	CH	water supply	production	1	unit	1E-11	64.1	32.6	3.3		
allocated products	disposal, digester sludge, to incineration, future, allocation price	CH	waste management	municipal incineration	0	kg	1	100.0	0.0	0.0	-1.7%	-0.017224003
	heat, digester sludge, at incineration plant, future, allocation price	CH	waste management	municipal incineration	0	MJ	0.2264	0.0	100.0	0.0	0.0%	0
	electricity, digester sludge, at incineration plant, future, alloc. price	CH	waste management	municipal incineration	0	kWh	0.0022	0.0	0.0	100.0	0.0%	0
Carbon Balance	Biogenic Carbon input					kg	0.000	0.000	0.000	0.000	totals	0.000
	Biogenic Carbon output in products					kg	-0.017	-0.017	0.000	0.000		-0.017
	Biogenic Carbon emissions, except CO2					kg	0.000	0.000	0.000	0.000		0.000
	Biogenic CO2 emissions					kg	0.017	0.017	0.000	0.000		0.017
	Carbon balance (inputs - outputs)						0.000	0.000	0.000	0.000		0.000

22.10 Life cycle inventory of raw sewage sludge incineration in municipal waste incinerator, current

In this life cycle inventory the incineration of raw sewage sludge in a current municipal waste incinerator is presented. The composition of raw sewage sludge, i.e. before biogas production in the fermenter, is adopted from (Doka 2003) (see Tab. 22.2 on page 630).

The system boundaries comprise dewatering of the sludge from a water content of 95% to 73%, disposal of the produced dewatering liquid, transport of the dewatered sludge to the incinerator, incineration expenditures, and landfilling of solid residues.

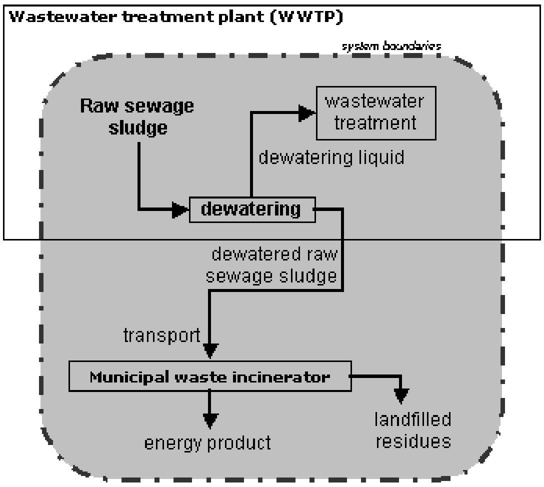

Fig. 22.7 System boundaries of raw sewage sludge incineration in municipal waste incinerator

It will be shown below, that no net energy can be produced from this process. Thus the dataset represents an unit process for disposal. The functional unit of the multi-output process 'disposal, raw sewage sludge, to municipal incineration' is 1 kilogram of wet raw sewage sludge with a water content of 95%.

Dewatering process and transport

Prior to incineration, the sludge is dewatered from 95% to 73% water content. Dewatering is included in this inventory to have comparable system boundaries to biogas from sewage sludge digestion (see chapter 4). Expenditures for dewatering are identical to those documented on page 643. Disposal of dewatering liquid is calculated by application of the existing calculation tool for municipal wastewater treatment described in (Doka 2003). In that tool, the full disposal chain of wastewater treatment is included by default (sewer transport, overload discharge, three-stage treatment in WWTP, sludge digestion and disposal of sludge). In order to assess the burdens created by internal treatment of dewatering liquid from raw sludge, only the burdens from 'three-stage treatment in WWTP' are heeded here, since the downstream fate of raw sludge is already being assessed.

After dewatering a transport per lorry 28t over 25 km to the incinerator is assumed.

Municipal waste incinerator

The incineration process is described qualitatively in chapter 22.5.3 'Municipal incineration process description' on page 632. Per functional unit of 1 kg wet raw sludge, approximately 180 grams of dewatered raw sludge are incinerated. The direct emissions from sludge incineration are calculated according to the calculated elemental composition of raw sludge after dewatering (waste-specific emissions). Exchanges are calculated with the existing ecoinvent calculation tool for municipal waste incineration provided in (Doka 2003). The incinerator technology represents the Swiss average for municipal incinerators in 2000.

Energy production

At a water content of 73%, the dewatered raw sludge has a lower heating value of 3.2 MJ/kg (Michel 1938). This is slightly higher than the heating value of digested sludge. Per functional unit (f.u.) only 179 grams dewatered sludge, or 0.57 MJ enter the MSWI. The incinerator converts that energy with a gross heat generation efficiency of 25.6% and a gross electricity generation efficiency of 13%, which represents the average efficiencies of Swiss MSWI in 2000. The internal energy consumption of the waste incinerator is 0.839 MJ heat and 0.144 kWh (0.518 MJ) electricity per kilogram incinerated waste (BUWAL 2001b), and proportionally less per functional unit. As shown in Tab. 22.24 in this average situation *no net energy* can be generated from dewatered raw sludge in an municipal waste incinerator.

Tab. 22.24 Energy generated from dewatered raw sludge in (current) municipal waste incinerator

Dewatered raw sludge lower heating value	MJ/kg	3.20	
Energy input per f.u.	MJ/f.u.	0.57	
		Heat	Electricity
Gross energy efficiency	%	25.57%	13.0%
Generated gross energy	MJ/f.u.	0.147	0.074
Internal consumption	MJ/kg	0.839	0.518
	MJ/f.u.	0.150	0.093
Generated net energy	MJ/f.u.	-0.0039	-0.01833

Allocation

As noted above, incineration of dewatered raw sludge in a (current) Swiss municipal waste incinerator generates no net energy. Thus, this process provides but only *one* useful service: disposal of raw sludge. No allocation is necessary. The dataset is created as a simple unit process inventory.

Tab. 22.25 Unit process raw data of 'disposal, raw sewage sludge, to municipal incineration'

Name	Location	Category	SubCategory	InfrastructureProcess	Unit	disposal, raw sewage sludge, to municipal incineration	biogenic carbon content in elementary flow	biogenic carbon flow
Location						CH		
InfrastructureProcess						0		
Unit						kg	kg/kg	kg/f.u.
Ammonium, ion	-	water	river	0	kg	0.000275772		
Nitrogen	-	water	river	0	kg	1.89298E-05		
NMVOC, non-methane volatile organic compounds, unspecified origin	-	air	high population density	0	kg	0		
Carbon monoxide, biogenic	-	air	high population density	0	kg	3.99677E-05	42.9%	1.7129E-05
Carbon dioxide, biogenic	-	air	high population density	0	kg	0.072598107	27.3%	0.019799484
Methane, biogenic	-	air	high population density	0	kg	1.14436E-06	75.0%	8.58268E-07
Sulfur dioxide	-	air	high population density	0	kg	3.96579E-06		
Nitrogen oxides	-	air	high population density	0	kg	6.74712E-05		
Ammonia	-	air	high population density	0	kg	1.68032E-06		
Dinitrogen monoxide	-	air	high population density	0	kg	9.79398E-06		
Cyanide	-	air	high population density	0	kg	1.90859E-06		
Phosphorus	-	air	high population density	0	kg	1.00659E-06		
Arsenic	-	air	high population density	0	kg	9.3261E-16		
Cadmium	-	air	high population density	0	kg	3.57826E-12		
Cobalt	-	air	high population density	0	kg	1.18931E-14		
Chromium	-	air	high population density	0	kg	2.09425E-13		
Copper	-	air	high population density	0	kg	9.6243E-11		
Mercury	-	air	high population density	0	kg	2.24421E-15		
Manganese	-	air	high population density	0	kg	6.68213E-14		
Molybdenum	-	air	high population density	0	kg	4.43387E-10		
Nickel	-	air	high population density	0	kg	5.2624E-14		
Lead	-	air	high population density	0	kg	1.34076E-10		
Tin	-	air	high population density	0	kg	1.23342E-09		
Zinc	-	air	high population density	0	kg	5.80285E-10		
Silicon	-	air	high population density	0	kg	3.21659E-06		
Iron	-	air	high population density	0	kg	2.08292E-07		
Calcium	-	air	high population density	0	kg	3.90838E-06		
Aluminum	-	air	high population density	0	kg	1.08197E-06		
Magnesium	-	air	high population density	0	kg	3.62452E-07		
BOD5, Biological Oxygen Demand	-	water	river	0	kg	6.95928E-05		
COD, Chemical Oxygen Demand	-	water	river	0	kg	0.000233691		
TOC, Total Organic Carbon	-	water	river	0	kg	5.46658E-05	100.0%	5.46658E-05
DOC, Dissolved Organic Carbon	-	water	river	0	kg	5.46658E-05		
Sulfate	-	water	river	0	kg	0.000506623		
Nitrate	-	water	river	0	kg	0.001278738		
Phosphate	-	water	river	0	kg	1.43815E-05		
Chloride	-	water	river	0	kg	5.69556E-05		
Arsenic, ion	-	water	river	0	kg	4.12202E-08		
Cadmium, ion	-	water	river	0	kg	2.94692E-11		
Cobalt	-	water	river	0	kg	6.40794E-11		
Chromium VI	-	water	river	0	kg	9.22844E-08		
Copper, ion	-	water	river	0	kg	5.29431E-10		
Mercury	-	water	river	0	kg	6.94877E-10		
Manganese	-	water	river	0	kg	6.86587E-10		
Molybdenum	-	water	river	0	kg	3.78639E-08		
Nickel, ion	-	water	river	0	kg	7.64768E-10		
Lead	-	water	river	0	kg	1.00617E-10		
Tin, ion	-	water	river	0	kg	3.44981E-11		
Zinc, ion	-	water	river	0	kg	6.53059E-09		
Silicon	-	water	river	0	kg	2.92781E-07		
Iron, ion	-	water	river	0	kg	2.13511E-06		
Calcium, ion	-	water	river	0	kg	8.86292E-06		
Aluminum	-	water	river	0	kg	5.76307E-08		
Magnesium	-	water	river	0	kg	9.21461E-07		
Chromium, ion	-	water	river	0	kg	9.02694E-09		
BOD5, Biological Oxygen Demand	-	water	ground-, long-term	0	kg	0.000160781		
COD, Chemical Oxygen Demand	-	water	ground-, long-term	0	kg	0.000491538		
TOC, Total Organic Carbon	-	water	ground-, long-term	0	kg	0.000194503	100.0%	0.000194503
DOC, Dissolved Organic Carbon	-	water	ground-, long-term	0	kg	0.000194503		
Sulfate	-	water	ground-, long-term	0	kg	0.002334735		
Nitrate	-	water	ground-, long-term	0	kg	7.61806E-05		
Phosphate	-	water	ground-, long-term	0	kg	0.000117887		
Arsenic, ion	-	water	ground-, long-term	0	kg	5.02121E-08		
Cadmium, ion	-	water	ground-, long-term	0	kg	6.51999E-10		
Cobalt	-	water	ground-, long-term	0	kg	3.2796E-07		
Chromium VI	-	water	ground-, long-term	0	kg	2.9983E-07		
Copper, ion	-	water	ground-, long-term	0	kg	1.0539E-05		
Mercury	-	water	ground-, long-term	0	kg	3.3808E-09		
Manganese	-	water	ground-, long-term	0	kg	1.05676E-05		
Molybdenum	-	water	ground-, long-term	0	kg	1.83383E-07		
Nickel, ion	-	water	ground-, long-term	0	kg	1.1416E-06		
Lead	-	water	ground-, long-term	0	kg	2.57349E-07		
Tin, ion	-	water	ground-, long-term	0	kg	4.67404E-07		
Zinc, ion	-	water	ground-, long-term	0	kg	5.50705E-07		
Silicon	-	water	ground-, long-term	0	kg	0.000119977		
Iron, ion	-	water	ground-, long-term	0	kg	0.002922459		
Calcium, ion	-	water	ground-, long-term	0	kg	0.002040277		
Aluminum	-	water	ground-, long-term	0	kg	0.00051255		
Magnesium	-	water	ground-, long-term	0	kg	0.000242984		
municipal waste incineration plant	CH	waste management	municipal incineration	1	unit	4.4827E-11		
process-specific burdens, municipal waste incineration	CH	waste management	municipal incineration	0	kg	0.179307879		
slag compartment	CH	waste management	municipal incineration	1	unit	3.28854E-11		
process-specific burdens, slag compartment	CH	waste management	municipal incineration	0	kg	0.018498033		
residual material landfill facility	CH	waste management	residual material landfill	1	unit	6.39288E-12		
process-specific burdens, residual material landfill	CH	waste management	residual material landfill	0	kg	0.003068583		
Heat, waste	-	air	high population density	0	MJ	0.80523531		
Heat, waste	-	water	river	0	MJ	0.231390036		
electricity from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	kWh	0.005090771		
heat from waste, at municipal waste incineration plant	CH	waste management	municipal incineration	0	MJ	0.003858058		
sodium hydroxide, 50% in H2O, production mix, at plant	RER	chemicals	inorganics	0	kg	0.000348504		
quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.002334778		
hydrochloric acid, 30% in H2O, at plant	RER	chemicals	inorganics	0	kg	3.84044E-07		
iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	0.001341112		
chemicals organic, at plant	GLO	chemicals	organics	0	kg	0.000262903		
chemicals inorganic, at plant	GLO	chemicals	inorganics	0	kg	6.40074E-07		
cement, unspecified, at plant	CH	construction materials	binder	0	kg	0.001227433		
disposal, cement, hydrated, 0% water, to residual material landfill	CH	waste management	residual material landfill	0	kg	0.003068583		
transport, freight, rail	RER	transport systems	train	0	tkm	0.00118646		
transport, lorry 28t	CH	transport systems	road	0	tkm	0.005549831		
ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	0.000106987		
natural gas, burned in industrial furnace low-NOx >100kW	RER	natural gas	heating systems	0	MJ	0.01043363		
titanium dioxide, production mix, at plant	RER	chemicals	inorganics	0	kg	3.06249E-06		
chromium oxide, flakes, at plant	RER	chemicals	inorganics	0	kg	6.24998E-08		
electricity, low voltage, at grid	CH	electricity	supply mix	0	kWh	0.00552862		
iron sulphate, at plant	RER	metals	extraction	0	kg	6.35336E-05		
aluminium sulphate, powder, at plant	RER	chemicals	inorganics	0	kg	1.7171E-05		
disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05		
disposal, paper, 11.2% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05		
wastewater treatment plant, class 3	CH	waste management	wastewater treatment	1	unit	4.66825E-12		
pump station	CH	water supply	production	1	unit	1E-11		
disposal, raw sewage sludge, to municipal incineration	CH	waste management	municipal incineration	0	kg	1	-2.0%	-0.020477491
Biogenic Carbon input					kg	0.000	totals	0.000
Biogenic Carbon output in products					kg	-0.020		-0.020
Biogenic Carbon emissions, except CO2					kg	0.000		0.000
Biogenic CO2 emissions					kg	0.020		0.020
Carbon balance (inputs - outputs)						0.000		0.000

22.11 Cumulative results and interpretation

22.11.1 Introduction

Selected LCI results and values for the cumulative energy demand (CED) are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht et al. (Frischknecht et al. 2004c). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

22.11.2 Heat from waste disposal

Selected LCI results and the cumulative energy demand for heat generation unit processes are shown in Tab. 22.26.

In general, the generation of heat from biowaste in a future municipal waste incinerator (2nd column) carries less burden than heat from biowaste in a current municipal waste incinerator (1st column) or heat from incineration of digested sludge in a future municipal waste incinerator. Incineration of raw or digested sludge in a current municipal waste incinerator does not produce any net heat.

Cumulative energy demand is chiefly composed of indirect energy demands, e.g. as used for infrastructure, auxiliary materials etc. Variations in CED figures in Tab. 22.26 are due to varying allocation factors for the disposal datasets and differing amounts of auxiliary materials, e.g. cement to solidify ash residues prior to landfilling. The cumulative energy demand does not include the energy content of the incinerated waste itself, since the system boundaries for these datasets do not include the production of the waste materials (cf. e.g. Fig. 22.2 on page 635). Therefore the waste heat emission is larger than the cumulative energy demand.

The LCI results contain the sum totals of all exchanges of all sub-categories[62]. The entry "Carbon dioxide, biogenic, total" contains the *net total*, i.e. all emissions of biogenic CO_2 *minus* CO_2 uptake from air. Of the biogenic CO_2 emitted during waste incineration, no part is allocated to the generated energy products (cf. chapter 'Carbon balance' on page 634). Therefore the net total for biogenic CO_2 is close to zero for all energy datasets. Minor amounts of CO_2 originate from background processes.

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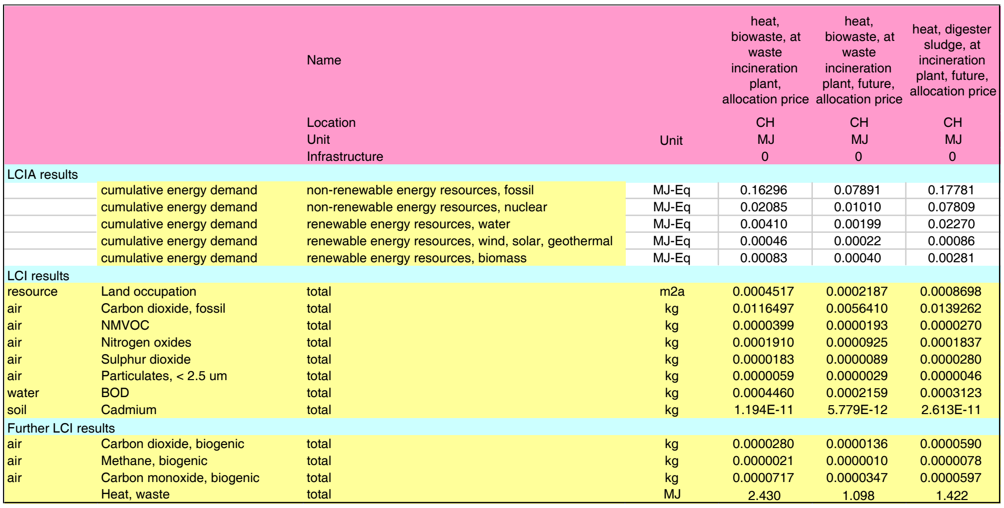
[62] For example, for air emissions the sum of all emissions to high population density air, low population density air, lower stratosphere + upper troposphere air, and unspecified air.

Tab. 22.26 Selected LCI results and the cumulative energy demand for the generation of heat from the disposal of biomass waste



		Name		heat, biowaste, at waste incineration plant, allocation price	heat, biowaste, at waste incineration plant, future, allocation price	heat, digester sludge, at incineration plant, future, allocation price
		Location		CH	CH	CH
		Unit	Unit	MJ	MJ	MJ
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.16296	0.07891	0.17781
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.02085	0.01010	0.07809
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.00410	0.00199	0.02270
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.00046	0.00022	0.00086
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00083	0.00040	0.00281
LCI results						
resource	Land occupation	total	m2a	0.0004517	0.0002187	0.0008698
air	Carbon dioxide, fossil	total	kg	0.0116497	0.0056410	0.0139262
air	NMVOC	total	kg	0.0000399	0.0000193	0.0000270
air	Nitrogen oxides	total	kg	0.0001910	0.0000925	0.0001837
air	Sulphur dioxide	total	kg	0.0000183	0.0000089	0.0000280
air	Particulates, < 2.5 um	total	kg	0.0000059	0.0000029	0.0000046
water	BOD	total	kg	0.0004460	0.0002159	0.0003123
soil	Cadmium	total	kg	1.194E-11	5.779E-12	2.613E-11
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	0.0000280	0.0000136	0.0000590
air	Methane, biogenic	total	kg	0.0000021	0.0000010	0.0000078
air	Carbon monoxide, biogenic	total	kg	0.0000717	0.0000347	0.0000597
	Heat, waste	total	MJ	2.430	1.098	1.422

Although the emissions from incineration are identical for the two multi-output processes referring to biowaste incineration (1st and 2nd column in Tab. 22.26) different burdens per MJ heat result in the unit processes. This is the result of dissimilar energy balances and thus allocation factors. The process producing *less* energy per kilogram biowaste (current incinerator, 1st column) carries *more* burden per megajoule than the process producing more energy (future incinerator, 2nd column), although the latter has a *larger* allocation factor on energy. The burden per megajoule ($B_{th.}$) equals the burden allocated to heat production divided by the amount net heat produced from one kilogram of biowaste (Q) and may be described as below.

$$B_{th.} = B_{MO} \Big/ \left(Q + \frac{r_D + r_{el.}}{p_{th.}} \right)$$

where

$B_{th.}$	Burden per megajoule heat
B_{MO}	Burden of multi-output process per 1kg biowaste
Q	Megajoule net heat from 1kg biowaste
r_D	revenue for disposal of 1kg biowaste
$r_{el.}$	revenue for electricity
$p_{th.}$	price per megajoule heat

Since the amount of produced heat Q is in the denominator, the burden per megajoule heat $B_{th.}$ will decrease with increasing heat production.

22.11.3 Electricity from waste disposal

Selected LCI results and the cumulative energy demand for electricity generation unit processes are shown in Tab. 22.27.

In general, the generation of electricity from biowaste in a future municipal waste incinerator (2nd column) carries less burden than electricity from biowaste in a current municipal waste incinerator (1st column) or electricity from incineration of digested sludge in a future municipal waste incinerator. Incineration of raw or digested sludge in a current municipal waste incinerator does not produce any net electricity.

Furthermore, the explanations made above for produced heat apply also to electricity.

Tab. 22.27 Selected LCI results and the cumulative energy demand for the generation of electricity from the disposal of biomass waste

		Name		electricity, biowaste, at waste incineration plant, allocation price	electricity, biowaste, at waste incineration plant, future, alloc. price	electricity, digester sludge, at incineration plant, future, alloc. price
		Location		CH	CH	CH
		Unit	Unit	kWh	kWh	kWh
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.71300	0.83123	1.86940
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.21920	0.10637	0.82096
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.04313	0.02093	0.23865
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.00486	0.00236	0.00907
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00871	0.00423	0.02959
LCI results						
resource	Land occupation	total	m2a	0.0047483	0.0023041	0.0091449
air	Carbon dioxide, fossil	total	kg	0.1224590	0.0594210	0.1464120
air	NMVOC	total	kg	0.0004197	0.0002036	0.0002835
air	Nitrogen oxides	total	kg	0.0020078	0.0009743	0.0019308
air	Sulphur dioxide	total	kg	0.0001928	0.0000935	0.0002941
air	Particulates, < 2.5 um	total	kg	0.0000625	0.0000303	0.0000485
water	BOD	total	kg	0.0046879	0.0022747	0.0032835
soil	Cadmium	total	kg	1.255E-10	6.088E-11	2.747E-10
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	0.0002948	0.0001431	0.0006204
air	Methane, biogenic	total	kg	0.0000217	0.0000105	0.0000820
air	Carbon monoxide, biogenic	total	kg	0.0007539	0.0003658	0.0006274
	Heat, waste	total	MJ	25.539	11.567	14.945

22.11.4 Biomass waste disposal

Selected LCI results and the cumulative energy demand for disposal unit processes are shown in Tab. 4.6.

In general, disposal of biowaste in a current municipal incinerator (1st column) carries more burden than disposal of biowaste in a future municipal incinerator (2nd column), since less burdens are allocated to energy generation. Disposal of digester sludge in a current municipal incinerator (3rd column) carries more burden than disposal of digester sludge in a future municipal incinerator (4th column), since only the latter process produces net energy, which bears some part of the total burden. Disposal of raw sludge in a current municipal incinerator (5th column) is close to the results for digester sludge (3rd column). Both process produce no net energy. The former has increased biogenic CO_2 emissions, since raw sludge contains more carbon than digester sludge. In the latter carbon has been removed during biogas production.

Tab. 22.28 Selected LCI results and the cumulative energy demand for the disposal of biomass waste

		Name		disposal, biowaste, 60% H2O, to municipal incineration, allocation price	disposal, biowaste, 60% H2O, to municipal incineration, future, alloc. price	disposal, digester sludge, to municipal incineration	disposal, digester sludge, to incineration, future, allocation price	disposal, raw sewage sludge, to municipal incineration
		Location		CH	CH	CH	CH	CH
		Unit	Unit	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0
LCIA results								
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.36213	0.17510	0.12392	0.07923	0.12723
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.04634	0.02241	0.05495	0.03479	0.05424
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.00912	0.00441	0.01599	0.01011	0.01583
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.00103	0.00050	0.00060	0.00038	0.00059
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00184	0.00089	0.00196	0.00125	0.00194
LCI results								
resource	Land occupation	total	m2a	0.0010038	0.0004853	0.0006057	0.0003876	0.0005584
air	Carbon dioxide, fossil	total	kg	0.0258879	0.0125172	0.0097028	0.0062049	0.0096322
air	NMVOC	total	kg	0.0000887	0.0000429	0.0000188	0.0000120	0.0000185
air	Nitrogen oxides	total	kg	0.0004244	0.0002052	0.0001281	0.0000818	0.0001497
air	Sulphur dioxide	total	kg	0.0000408	0.0000197	0.0000195	0.0000125	0.0000186
air	Particulates, < 2.5 um	total	kg	0.0000132	0.0000064	0.0000032	0.0000021	0.0000032
water	BOD	total	kg	0.0009910	0.0004792	0.0002171	0.0001392	0.0002434
soil	Cadmium	total	kg	2.652E-11	1.282E-11	1.825E-11	1.164E-11	1.711E-11
Further LCI results								
air	Carbon dioxide, biogenic	total	kg	0.5886179	0.5885903	0.0616409	0.0616260	0.0726340
air	Methane, biogenic	total	kg	0.0000046	0.0000022	0.0000054	0.0000035	0.0000012
air	Carbon monoxide, biogenic	total	kg	0.0001594	0.0000771	0.0000415	0.0000266	0.0000402
	Heat, waste	total	MJ	5.399	2.437	1.025	0.633	1.176

22.12 Conclusions

Multi-output datasets for the incineration of several types of biomass waste are generated. Process data is based on established inventory calculations for incineration in Swiss municipal waste incinerators, as descibed in (Doka 2003). For incineration in future waste incinerators new data was acquired regarding the energy balance, based on planning data for one Swiss municipal waste incinerator plant.

Datasets for disposal use a different allocation approach than former ecoinvent datasets. Care has to be taken if datasets for biomass waste disposal from this study are combined with earlier datasets for the disposal of other waste materials from (Doka 2003).

Abbreviations

BUWAL	The Swiss Environmental Protection Agency (Bundesamt für Umwelt, Wald und Landschaft). Name change to BAFU (Bundesamt für Umwelt) in 2005.
ESP	Electrostatic precipitator. A type of filter in flue gas cleaning.
f.u.	functional unit (unit of measure that a unit process inventory relates to)
kWh	Kilowatt-hour (1000 Watt hours)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule (1'000'000 joules)
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
SDG	(also SDg or GSD) geometric standard deviation. Measure of uncertainty, cf. (Frischknecht et al. 2003)
WWT	(municipal) wastewater treatment
WWTP	(municipal) wastewater treatment plant. Also called effluent treatment plant or sewage treatment plant (German: 'Kläranlage', Swiss German: 'Abwasser-Reinigungs-Anlage, ARA').

Glossary of terms

Biowaste	For the purposes of the bioenergy study, biowaste is fresh green waste i.e. wet kitchen and garden waste, like fruit and vegetable waste, grass cuttings, hedge trimmings, weeds and dead flowers. Other waste categories that could be considered bio(mass)waste like waste paper/cardboard, waste wood, dead animal or human remains, surgery waste.
Raw sludge	(Ger. 'Rohschlamm', 'Frischschlamm') Sludge from the wastewater treatment prior to anaerobic digestion. See also digested sludge.
Digested sludge	(Ger. 'Faulschlamm', 'Gärschlamm') Sludge from the wastewater treatment after anaerobic digestion/biogas production. See also raw sludge.
Sewage	Input to the WWTP, transported in sewers. Identical to 'wastewater'. The output of the WWTP is called 'effluent' or 'discharge'.

Appendices: EcoSpold Meta Information

Tab. A. 48 EcoSpold Meta Information of 'biowaste, to municipal incineration'

Type	**Field name, IndexNumber**	
ReferenceFunction	Name	biowaste, to municipal incineration
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	5
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	transport to incinerator. waste-specific air and water emisions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emisions to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber slugde). Process energy demands for MSWI.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Bioabfall, in Kehrichtverbrennung
ReferenceFunction	Synonyms	Grüngut//Grünabfall//Gartenabfälle//Küchenabfälle//Kompostierbares//garden waste//kitchen waste//compostable waste
ReferenceFunction	GeneralComment	Incinerated amount = 1kg. Incinerated waste contains 100% biowaste; . waste composition (wet, in ppm): upper heating value 6.82 MJ/kg; lower heating value 5.104 MJ/kg; H2O 600000; O 126430; H 20000; C 162400; S 1499.3; N 4000; P 1130; B 10.24; Cl 4000; Br 6; F 200; I 0.055; Ag n.a.; As 2; Ba n.a.; Cd 0.138; Co 5; Cr 8; Cu 18; Hg 0.07; Mn 4.3; Mo 0.4; Ni 5.42; Pb 18.56; Sb n.a.; Se 0.49976; Sn 7.9961; V 2.9985; Zn 58.24; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 39980; Fe 600; Ca 21800; Al 9995.1; K 3500; Mg 2820; Na 1500; Share of carbon in waste that is biogenic 100%. Share of iron in waste that is metallic/recyclable 0%. Net energy produced in MSWI: 0.15MJ/kg waste electric energy and 0.47MJ/kg waste thermal energy One kg of this waste produces 0.1337 kg of slag and 0.01883 kg of residues, which are landfilled. Additional solidification with 0.007533 kg of cement.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	waste management
ReferenceFunction	SubCategory	municipal incineration
ReferenceFunction	LocalCategory	Entsorgungssysteme
ReferenceFunction	LocalSubCategory	Kehrichtverbrennung
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	1994-01
TimePeriod	EndDate	2000-12
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	Waste composition as given in literature reference. Transfer coefficients for modern Swiss MSWI. Emission speciation based on early 90ies data.
Geography	Text	Specific to the technology mix encountered in Switzerland in 2000. Well applicable to modern incineration practices in Europe, North America or Japan.
Technology	Text	average Swiss MSWI plants in 2000 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR , 32.2% SCR-high dust , 24.6% SCR-low dust -DeNOx facilities and 13.8% without Denox (by burnt waste, according to Swiss average). Gross electric efficiency technology mix 12.997% and Gross thermal efficiency technology mix 25.57%
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	Typical elemental transfer coefficients from current studies for modern MSWI, completed with data from coal power plants and estimates, adapted for inert/burnable waste.
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

Tab. A. 49 EcoSpold Meta Information of 'biowaste, to municipal incineration, future'

Type	Field name, IndexNumber	
ReferenceFunction	Name	biowaste, to municipal incineration, future
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	5
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	transport to incinerator. waste-specific air and water emisions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emisisons to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber slugde). Process energy demands for (future) MSWI.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Bioabfall, in Kehrichtverbrennung, Zukunft
ReferenceFunction	Synonyms	Grüngut//Grünabfall//Gartenabfälle//Küchenabfälle//Kompostierbares//garden waste//kitchen waste//compostable waste
ReferenceFunction	GeneralComment	Incinerated amount = 1 kg . Incinerated waste contains 100% biowaste; . waste composition (wet, in ppm): upper heating value 6.82 MJ/kg; lower heating value 5.104 MJ/kg; H2O 600000; O 126430; H 20000; C 162400; S 1499.3; N 4000; P 1130; B 10.24; Cl 4000; Br 6; F 200; I 0.055; Ag n.a.; As 2; Ba n.a.; Cd 0.138; Co 5; Cr 8; Cu 18; Hg 0.07; Mn 4.3; Mo 0.4; Ni 5.42; Pb 18.56; Sb n.a.; Se 0.49976; Sn 7.9961; V 2.9985; Zn 58.24; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 39980; Fe 600; Ca 21800; Al 9995.1; K 3500; Mg 2820; Na 1500; Share of carbon in waste that is biogenic 100%. Share of iron in waste that is metallic/recyclable 0%. Net energy produced in MSWI: 0.49MJ/kg waste electric energy and 2.77MJ/kg waste thermal energy One kg of this waste produces 0.1337 kg of slag and 0.01883 kg of residues, which are landfilled. Additional solidification with 0.007533 kg of cement.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	waste management
ReferenceFunction	SubCategory	municipal incineration
ReferenceFunction	LocalCategory	Entsorgungssysteme
ReferenceFunction	LocalSubCategory	Kehrichtverbrennung
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	2010
TimePeriod	EndDate	2020
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	Waste composition as given in literature reference. Transfer coefficients for modern Swiss MSWI. Emission speciation based on early 90ies data.
Geography	Text	Based on planing data for modernisation of a Swiss MSWI plant
Technology	Text	Based on average Swiss MSWI plants in 2000 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR , 32.2% SCR-high dust , 24.6% SCR-low dust -DeNOx facilities and 13.8% without Denox (by burnt waste, according to Swiss average). Modernised (future) energy production. Gross electric efficiency technology mix 16.7% and Gross thermal efficiency technology mix 56.3%
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	Typical elemental transfer coefficients from current studies for modern MSWI, completed with data from coal power plants and estimates, adapted for inert/burnable waste.
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

Tab. A. 50 EcoSpold Meta Information of ' disposal, digester sludge, to municipal incineration'

Type	Field name, IndexNumber	
ReferenceFunction	Name	disposal, digester sludge, to municipal incineration
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	1
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	dewatering of sludge. treatment of dewatering liquid. transport of dewatered sludge to incinerator. waste-specific air and water emisions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emisisons to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber slugde). Process energy demands for MSWI.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Entsorgung, Klärfaulschlamm, in Kehrichtverbrennung
ReferenceFunction	Synonyms	Vergärter Klärschlamm der Kläranlage//Gärschlamm//fermented sewage sludge
ReferenceFunction	GeneralComment	Incinerated amount = 0.1793kg. Incinerated waste contains 100% digested sludge, 73% H2O; . waste composition (wet, in ppm): upper heating value 4.257 MJ/kg; lower heating value 2.421 MJ/kg; H2O 730000; O 51118; H 11618; C 92941; S 6170.9; N 5783.7; P 8623.9; B n.a.; Cl n.a.; Br n.a.; F n.a.; I n.a.; Ag n.a.; As 0.77881; Ba n.a.; Cd 0.5542; Co 3.1948; Cr 24.157; Cu 111.2; Hg 0.5542; Mn 104.67; Mo 1.8908; Ni 10.399; Pb 30.807; Sb n.a.; Se n.a.; Sn 7.9304; V n.a.; Zn 302.95; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 11784; Fe 53213; Ca 19996; Al 5907.2; K n.a.; Mg 2245; Na n.a.; Share of carbon in waste that is biogenic 100%. Share of iron in waste that is metallic/recyclable 0%. Net energy produced in MSWI: 0MJ/kg waste electric energy and 0MJ/kg waste thermal energy One kg of this waste produces 0.1543 kg of slag and 0.02427 kg of residues, which are landfilled. Additional solidification with 0.009707 kg of cement.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	waste management
ReferenceFunction	SubCategory	municipal incineration
ReferenceFunction	LocalCategory	Entsorgungssysteme
ReferenceFunction	LocalSubCategory	Kehrichtverbrennung
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	1994-01
TimePeriod	EndDate	2000-12
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	Waste composition as given in literature reference. Transfer coefficients for modern Swiss MSWI. Emission speciation based on early 90ies data.
Geography	Text	Specific to the technology mix encountered in Switzerland in 2000. Well applicable to modern incineration practices in Europe, North America or Japan.
Technology	Text	average Swiss MSWI plants in 2000 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR , 32.2% SCR-high dust , 24.6% SCR-low dust - DeNOx facilities and 13.8% without Denox (by burnt waste, according to Swiss average). Gross electric efficiency technology mix 12.997% and Gross thermal efficiency technology mix 25.57%
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	Typical elemental transfer coefficients from current studies for modern MSWI, completed with data from coal power plants and estimates, adapted for inert/burnable waste.
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

Tab. A. 51 EcoSpold Meta Information of 'digester sludge, to municipal incineration, future'

Type	Field name, IndexNumber	
ReferenceFunction	Name	digester sludge, to municipal incineration, future
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	5
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	dewatering of sludge. treatment of dewatering liquid. transport of dewatered sludge to incinerator. waste-specific air and water emisions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emisisons to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Klärfaulschlamm, in Kehrichtverbrennung, Zukunft
ReferenceFunction	Synonyms	Vergärter Klärschlamm der Kläranlage//Gärschlamm//fermented sewage sludge
ReferenceFunction	GeneralComment	Incinerated amount = 0.1793 kg. Functional unit refers to 1 kilogram wet sludge with 95% water. Incinerated waste contains 100% digested sludge, 73% H2O; . waste composition (wet, in ppm): upper heating value 4.257 MJ/kg; lower heating value 2.421 MJ/kg; H2O 730000; O 51118; H 11618; C 92941; S 6170.9; N 5783.7; P 8623.9; B n.a.; Cl n.a.; Br n.a.; F n.a.; I n.a.; Ag n.a.; As 0.77881; Ba n.a.; Cd 0.5542; Co 3.1948; Cr 24.157; Cu 111.2; Hg 0.5542; Mn 104.67; Mo 1.8908; Ni 10.399; Pb 30.807; Sb n.a.; Se n.a.; Sn 7.9304; V n.a.; Zn 302.95; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 11784; Fe 53213; Ca 19996; Al 5907.2; K n.a.; Mg 2245; Na n.a.; Share of carbon in waste that is biogenic 100%. Share of iron in waste that is metallic/recyclable 0%. Net energy produced in MSWI: 0.04MJ/kg waste electric energy and 1.26MJ/kg waste thermal energy One kg of this waste produces 0.1543 kg of slag and 0.02427 kg of
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	waste management
ReferenceFunction	SubCategory	municipal incineration
ReferenceFunction	LocalCategory	Entsorgungssysteme
ReferenceFunction	LocalSubCategory	Kehrichtverbrennung
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	2010
TimePeriod	EndDate	2020
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	Waste composition as given in literature reference. Transfer coefficients for modern Swiss MSWI. Emission speciation based on early 90ies data.
Geography	Text	Based on planing data for modernisation of a Swiss MSWI plant
Technology	Text	Based on average Swiss MSWI plants in 2000 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR , 32.2% SCR-high dust , 24.6% SCR-low dust -DeNOx facilities and 13.8% without Denox (by burnt waste, according to Swiss average). Modernised (future) energy production. Gross electric efficiency technology mix 16.7% and Gross thermal efficiency technology mix 56.3%
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	Typical elemental transfer coefficients from current studies for modern MSWI, completed with data from coal power plants and estimates, adapted for inert/burnable waste.
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

Tab. A. 52 EcoSpold Meta Information of ' disposal, raw sewage sludge, to municipal incineration'

Type	Field name, IndexNumber	
ReferenceFunction	Name	disposal, raw sewage sludge, to municipal incineration
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	1
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	dewatering of sludge. treatment of dewatering liquid. transport of dewatered sludge to incinerator. waste-specific air and water emisions from incineration, auxiliary material consumption for flue gas cleaning. Short-term emissions to river water and long-term emisisons to ground water from slag compartment (from bottom slag) and residual material landfill (from solidified fly ashes and scrubber slugde). Process energy demands for MSWI.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Entsorgung, Klärfrischschlamm, in Kehrichtverbrennung
ReferenceFunction	Synonyms	Unvergärter Rohschlamm der Kläranlage//unfermented sewage sludge
ReferenceFunction	GeneralComment	Incinerated amount = 0.1793kg. Incinerated waste contains 100% raw sludge, 73% H2O; . waste composition (wet, in ppm): upper heating value 5.077 MJ/kg; lower heating value 3.196 MJ/kg; H2O 730000; O 61097; H 13886; C 111090; S 5191.6; N 11827; P 5613.7; B n.a.; Cl n.a.; Br n.a.; F n.a.; I n.a.; Ag n.a.; As 0.50992; Ba n.a.; Cd 0.36239; Co 2.0891; Cr 15.796; Cu 72.712; Hg 0.36239; Mn 68.441; Mo 1.2364; Ni 6.8001; Pb 20.145; Sb n.a.; Se n.a.; Sn 5.1856; V n.a.; Zn 198.1; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 7705.6; Fe 34796; Ca 13075; Al 3862.6; K n.a.; Mg 1468; Na n.a.; Share of carbon in waste that is biogenic 100%. Share of iron in waste that is metallic/recyclable 0%. Net energy produced in MSWI: 0MJ/kg waste electric energy and 0MJ/kg waste thermal energy One kg of this waste produces 0.1032 kg of slag and 0.01711 kg of residues, which are landfilled. Additional solidification with 0.006845 kg of cement.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	waste management
ReferenceFunction	SubCategory	municipal incineration
ReferenceFunction	LocalCategory	Entsorgungssysteme
ReferenceFunction	LocalSubCategory	Kehrichtverbrennung
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	1994-01
TimePeriod	EndDate	2000-12
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	Waste composition as given in literature reference. Transfer coefficients for modern Swiss MSWI. Emission speciation based on early 90ies data.
Geography	Text	Specific to the technology mix encountered in Switzerland in 2000. Well applicable to modern incineration practices in Europe, North America or Japan.
Technology	Text	average Swiss MSWI plants in 2000 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 29.4% SNCR , 32.2% SCR-high dust , 24.6% SCR-low dust - DeNOx facilities and 13.8% without Denox (by burnt waste, according to Swiss average). Gross electric efficiency technology mix 12.997% and Gross thermal efficiency technology mix 25.57%
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	Typical elemental transfer coefficients from current studies for modern MSWI, completed with data from coal power plants and estimates, adapted for inert/burnable waste.
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

Appendix: Alternative Data for Future Municipal Waste Incinerator

In the present study, allocation factors are calculated depending on net energy production during waste incineration. The internal energy demand in municipal waste incinerators is modelled to be constant for every kilogram of waste In a similar study on biowaste incineration in future municipal waste incinerators (ERZ 2006) a different approach was used, see chapter 'Energy production' on page 639. Alternative allocation factors for the incineration of biowaste, based on the approach presented in (ERZ 2006) are shown below.

In (ERZ 2006) the internal energy demands for the processing of one kilogram of a particular waste fraction are assumed to be *proportional to the lower heating* value of that waste. Tab. 22.29 shows the resulting energy demands for biowaste. The alternative internal energy demands lead to different net energy production (compare to 'Tab. 22.11' on page 640). Tab. 22.30 shows the resulting net energy production for biowaste. The alternative net energy production leads to different allocation factors (compare to 'Tab. 22.12' on page 641). Tab. 22.30 shows the resulting alternative allocation factors for biowaste incineration.

As explained in chapter 'Energy production' on page 639, *both* approaches of (Doka 2003) and (ERZ 2006) *underestimate* the internal heat consumption for biowaste and thus overestimate net heat production from biowaste. If internal heat energy consumption were differentiated according to the different causes in the municipal incinerator, the allocation factors on sold heat would probably be much lower than either in Tab. 22.12 or Tab. 22.30.

Tab. 22.29 Alternative internal energy energy demand for incineration of one kilogram of biowaste in future municipal waste incinerator

Average municipal waste lower heating value	MJ/kg	12.96 [1]	
Biowaste lower heating value	MJ/kg	5.1	
		Heat	Electricity
Internal energy consumption for average waste (cf. 'Tab. 22.11' on page 640)	MJ/kg	0.099	0.36
Internal energy consumption for biowaste (proportional to biowaste lower heating value)	MJ/kg	0.039	0.142

[1] Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), April 3, 2006.

Tab. 22.30 Alternative date for energy generated from one kilogram of biowaste in future municipal waste incinerator

Biowaste lower heating value	MJ/kg	5.1	
		Heat	Electricity
Gross energy efficiency	%	56.3%	16.7%
Generated gross energy	MJ/kg	2.87	0.852
Alternative internal energy consumption according to (ERZ 2006)	MJ/kg	**0.039**	**0.142**
Generated net energy	MJ/kg	2.832	0.7107 (2.56 kWh/kg)

Tab. 22.31 Alternative set of revenues generated from one kilogram of biowaste in (future) municipal waste incinerator

Per kilogram biowaste	*Disposal service*	*Sold heat*	*Sold electricity*
Valued amounts	1 kg	2.832 MJ	0.7107 MJ
Fees and prices [1]	0.2 CHF/kg	0.09 CHF/MJ	0.2628 CHF/MJ
Generated revenues	0.2 CHF	0.255 CHF	0.187 CHF
Alternative allocation keys	**31.2%** **on disposal service**	**39.7%** **on heat production**	**29.1%** **on electricity production**

1 Fees and prices are identical to Tab. 22.8 on page 636.

References

Althaus et al. 2004	Althaus H.-J., Chudacoff M., Hellweg S., Hischier R., Jungbluth N., Osses M. Primas A. (2004) Life cycle inventories of chemicals. ecoinvent report No. 8. Swiss Centre for Life Cycle Inventories, Duebendorf, 2004
BFE 2005	Kaufmann U. (2005) Schweizerische Statistik der erneuerbaren Energien 2004. Dr. Eicher+Pauli AG, Commissioned by BFE Bundesamt für Energie, August 2005. Retrieved March 27, 2006 from http://www.bfe.admin.ch/php/modules/publikationen/stream.php?extlang=de&name=de_767884095.pdf&endung=Schweizerische%20Statistik%20der%20erneuerbaren%20Energien%202004
Böhler et al. 2003	Böhler M., Siegrist H., Pinnow D., Müller D., Krauss W., Brauchli H. (2003) Neue Presstechnologie zur verbesserten Klärschlammentwässerung Schlussbericht zu den Untersuchungen auf der ARA Glarnerland (AVG) . EAWAG Swiss Federal Institute for Environmental Science and Technology, Dübendorf, Switzerland. Retrieved March 16, 2006 from http://www.bucherguyer.ch/foodtech/klaerschlammentwaesserung__bucher_presse_d-4.pdf
BUWAL 2001a	BUWAL (2001) Entsorgung des Klärschlammms 2000, Stand 11.12.2001, BUWAL, Berne, Switzerland. Retrieved March 2, 2002 from http://www.buwal.ch/abfall/docu/pdf/tab15_d.pdf
BUWAL 2001b	BUWAL (2001) Brennbare Abfälle in KVA und auf Deponien 2000, Stand 11.12.2001, BUWAL Industrie- und Gewerbeabfälle, Berne, Switzerland Retrieved March 2, 2002 from http://www.buwal.ch/abfall/docu/pdf/tab3_d.pdf
BUWAL 2001c	BUWAL (2001) Anlieferungen in KVA 2000, Stand 11.12.2001. BUWAL Industrie- und Gewerbeabfälle, Berne, Switzerland Retrieved March 2, 2002 from http://www.buwal.ch/abfall/docu/pdf/tab6_d.pdf
BUWAL 2004a	Laube A., Vonplon A. (2004) Klärschlammentsorgung in der Schweiz – Mengen- und Kapazitätserhebung. Umwelt-Materialien Nr. 181, BUWAL, Berne, Switzerland. Retrieved April 21, 2006 from http://www.umwelt-schweiz.ch/imperia/md/content/abfall/ks_bericht_d.pdf
BUWAL 2004b	BUWAL (2004) Entsorgung des Klärschlammms 2002, Stand 7.8.2004, BUWAL, Berne, Switzerland. Retrieved June 5, 2005 from http://www.umwelt-schweiz.ch/imperia/md/content/abfall/tab17-02_d.pdf
Dettli et al. 2004	Dettli R., Steiner P., Baur M., Müller M. (2004) Kosten und Entschädigung von Strom aus Kehrichtverbrennungsanlagen. Econcept, Zurich, commissioned by Bundesamt für Energie BFE, Berne. Retrieved February 14, 2006 from http://www.vpe.ch/pdf/STROM-Kehricht.pdf
Doka 2003	Doka G. (2003) Life Cycle Inventories of Waste Treatment Services. Final report ecoinvent 2000 No. 13. EMPA St. Gallen, Swiss Centre for Life Cycle Invento-ries, Dübendorf, CH

ERZ 2006	Entsorgung + Recycling Zürich (Ed.) (2006) Verwertung der biogenen Abfälle in der Stadt Zürich – Bericht mit besonderer Berücksichtigung der biogenen Abfälle aus Haushalten. ERZ Entsorgung + Recycling Zürich (Zurich Municipal Waste Management Services). Retrieved April 7, 2006 from http://www.stadt-zuerich.ch/internet/erz/home/khkw/Biogene_Abfaelle.ParagraphContainerList.ParagraphContainer1.ParagraphList.0002.File.pdf/Bericht%20Biogene%20Abfälle%20der%20STZH%20Publikation%20Druckversion.pdf (see also http://www.stadt-zuerich.ch/internet/erz/home/khkw/Biogene_Abfaelle.html)
Fasel 2006	Fasel A. (2006) Technischer Bericht 2005. ARA Region Bern AG, Berne. Retrieved March 26, 2006 from http://www.ara-bern.ch/d/pdf/tech_bericht_01.pdf
Frischknecht et al. 2004a	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2004a) Overview and Methodology. Final report ecoinvent 2000 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
Frischknecht et al. 2004c	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004c) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
Iten et al. 2001	Iten R., Pulli R., Roduit J. (2001) Umweltbezogene Abgaben in der Schweiz 1990–2000. Bundesamt für Statistik, Neuchatel, Switzerland. Retrieved February 14, 2006 from http://www.bfs.admin.ch/bfs/portal/de/index/themen/raum_und_umwelt/uebersicht/blank/publikationen.Document.26218.html
Kettler 2003	Kettler R. (2003) Country Report Switzerland – Biowaste production and treatment. BUWAL. Excerpt of the report "Status and Trends for Biological Treatment of Waste in Europe" by ISWA (International Solid Waste Association). Retrieved April 20, 2006 from http://www.umwelt-schweiz.ch/imperia/md/content/abfall/iswareport_e.pdf
Liebi 2002	Liebi C. (2002) Umweltbericht 2001 Kläranlage Kloten/Opfikon. Glattbrugg, Switzerland. Retrieved December 28, 2002 from http://www.klaeranlage.ch/download/Umweltbericht%202001.pdf
Michel 1938	Michel R. (1938) Berechnung der Verbrennungswärmen fester und flüssiger Brennstoffe nach den Wärmewerten ihrer Einzelbestandteile. Feuerungstechnik 26, No.9, p.273-278 (Leipzig, Germany. Appeared 1912 –1943).
Moser 2006	Moser R. (2006) Zustand der Abwasserreinigungsanlagen in der Schweiz: Handlungsbedarf. Gebr. Hunziker AG, Winterthur. Im Rahmen der Fachveranstaltung 'Instandsetzung von Abwasserreinigungsanlagen und begehbaren Kanälen. 30 März 2006' Bau und Wissen Nr. 854572, Wildegg. Retrieved April 3, 2006 from http://www.hunzikerwater.ch/downloads/854571%20Referat.pdf
Siegrist 2006	Siegrist H. (2006) Biological treatment of high strength ammonia waste waters. Eawag Environmental Engineering, Duebendorf, Switzerland. Retrieved March 26, 2006 from http://www.eawag.ch/research_e/ing/VT_proc_engineering/fux/e_faulwasser.htm

23 Incineration Sewage Sludge in Cement Kiln

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Review: Niels Jungbluth, ESU-services, Uster
Last changes: June 2006

Remark: This dataset is not included in ecoinvent data v2.0. It has been investigated in the framework of the project "Ökobilanz von Energieprodukten" and was part of the LCIA done in the second part of this project.

Summary

A life cycle inventory of the incineration of raw (undigested) sewage sludge in a Swiss cement kiln is presented. The process is treated as a multi-output process with the disposal service on one hand, and energy utilisation for the cement clinkering process. Allocation with economical parameters is applied.

Included processes are dewatering, transport to incineration facility, and drying. Functional units of disposal datasets refer to one kilogram of wet waste, i.e. for sewage sludge before dewatering. The net energy production is inventoried per megajoule for heat.

23.1 Introduction

In this chapter 23 life cycle inventory data and the underlying assumptions for the incineration of raw (undigested) sewage sludge in a Swiss cement kiln are presented.

23.2 Reserves and Resources of Sewage Sludge

Reserves and resources of sewage sludge are outlined in chapter 22 'Incineration of Biowaste and Sewage Sludge'.

23.3 Characterisation of sewage sludge

Sewage sludge is the slurry residue from *municipal wastewater treatment*, i.e. stems from municipal sewage. Most sewage sludge in Switzerland is digested (fermented) sludge, i.e. has already been used to produce biogas[63]. In this chapter, raw (undigested) sludge is considered, such as produced for example by small scale wastewater treatment plants. Fresh wastewater treatment sludge has normally a very high water content of 94 – 96 w-%. Prior to incineration the sludge is therefore mechanically dewatered to approximately 70-75% water content, and in the case of cement kiln incineration additionally dried to approximately 10% water content, to reduce transport expenditures and augment fuel qualities (BUWAL 2004a:18).

The composition of raw sludge is based on data from (Doka 2003) and represents a generic composition of Swiss sewage sludge.

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[63] Personal communication with Max Maurer, EAWAG Dübendorf, March 5, 2002.

Tab. 23.1 Initial composition of raw sewage sludge.

			Raw sewage sludge adapted from (Doka 2003)
lower heating value	H_u	MJ/kg	-1.202
Water content	H_2O	%	95%
Oxygen	O	kg/kg	0.01126
Hydrogen	H	kg/kg	0.00256
Carbon	C	kg/kg	0.02048
Sulfur	S	kg/kg	0.0009309
Nitrogen	N	kg/kg	0.002758
Phosphor	P	kg/kg	0.00102
Boron	B	ppm	-
Chlorine	Cl	ppm	-
Bromium	Br	ppm	-
Fluorine	F	ppm	-
Iodine	I	ppm	-
Arsenic	As	ppm	0.09143
Cadmium	Cd	ppm	0.06498
Cobalt	Co	ppm	0.3746
Chromium	Cr	ppm	2.832
Copper	Cu	ppm	13.04
Mercury	Hg	ppm	0.06498
Manganese	Mn	ppm	12.27
Molybdenum	Mo	ppm	0.2217
Nickel	Ni	ppm	1.219
Lead	Pb	ppm	3.612
Selenium	Se	ppm	-
Tin	Sn	ppm	0.9298
Vanadium	V	ppm	-
Zinc	Zn	ppm	35.52
Silicon	Si	ppm	1382
Iron	Fe	ppm	6239
Calcium	Ca	ppm	2345
Aluminium	Al	ppm	692.6
Potassium	K	ppm	-
Magnesium	Mg	ppm	263.2
Sodium	Na	ppm	-

23.4 Use of Sewage Sludge

Spreading of sewage sludge on agricultural fields is completely prohibited in Switzerland as of October 2006. The target disposal route is incineration, where some energy might be gained. Current disposal routes of sewage sludge are outlined in chapter 22 'Incineration of Biowaste and Sewage Sludge'.

23.5 System characterisation

23.5.1 Characterization of unit processes

The dataset relates to one kilogram of waste material. Like with other waste disposal processes in the ecoinvent database, mass refers to a *wet composition* and not dry content. Raw sewage sludge is assumed to have an initial water content of 95% (see Tab. 22.2 on page 630). Sewage sludge is assumed to be dewatered and dried before incineration. The functional unit of the dataset refers to 1 kg *wet sewage sludge* with 95% water content.

23.5.2 Sludge dewatering process description

Before incineration some of the water in sludge is usually removed, since sludge with 95% water cannot burn by itself. Sludge dewatering (or sludge drainage) is a common process in wastewater treatment plants (WWTP). The weight reduction is approximately 80% and thus transport costs are reduced. Sludge dewatering reduces the water content of sewage sludge from approximately 95% to 73%. This is usually performed by addition of flocculation agents, to help formation of large particles, followed by mechanical dewatering processes like centrifuges, belt filters (pressure filtration), or membrane filters.

Dewatering produces a liquid rich in ammonia. Approximately 20% – 40% of the nitrogen is removed from the sludge input by this route. This liquid is recycled internally into the WWT process or treated separately. Also some carbon and phosphorus compounds are removed with the dewatering liquid.

23.5.3 Sludge drying process description

Before incineration in cement kilns sludge will not only be dewatered, but subsequently also dried to about 10% water content, because the kiln process requires dry fuels. Drying is achieved by heating up the dewatered sludge with heating elements or by mixing it with hot air. Also solar sludge drying is possible. In this study only drying with fossil fuels is considered.

The resulting weight changes from water removal and drying of 1000 kg wet raw sludge are shown in Tab. 23.2. The functional unit of the datasets is 1 kg of wet raw sludge (i.e. with 95% water). Tab. 23.2 establishes the compatible relations between different materials. Please note, that some dry substance is removed by way of dewatering liquid.

Tab. 23.2 Weight changes resulting from water removal for 1000 kg wet raw sludge.

Sludge Type	Water content	**Raw sludge** (wet weight)
Wet sludge	95%	1000 kg
		↓
Dewatered sludge [1]	73%	179.3 kg
		↓
Dried sludge	10%	53.79 kg

[1] Difference to wet sludge is removed dewatering liquid, containing approximately 1933 ppm dry substance.

23.5.4 Cement kiln incineration process description

The production of cement starts with preparation of the raw materials, like limestone, chalk, marl and other quarried virgin (or primary) raw material. These materials are increasingly replaced by secondary materials like fly ash, mill scale, metal smelting slag, pyrite cinder lime sludge, building rubble, sludge and moulding sand.

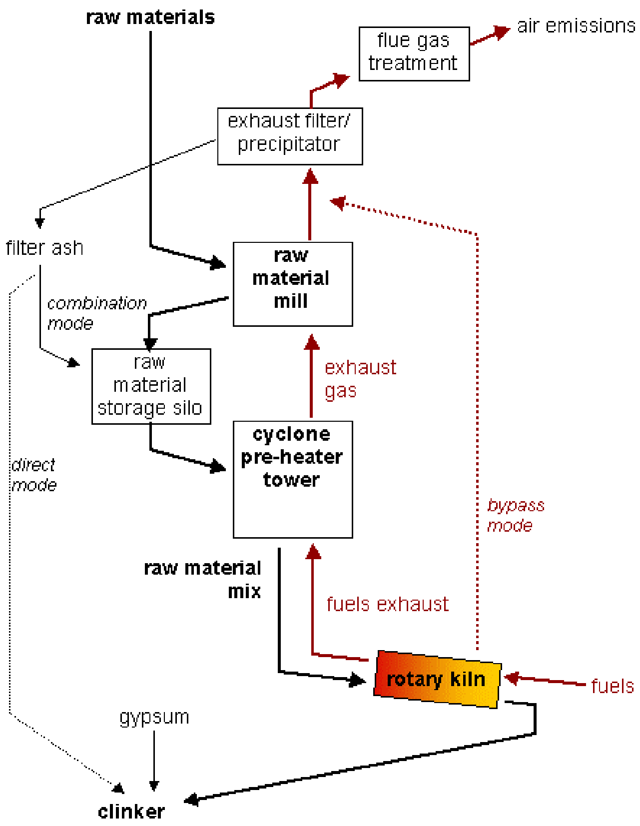

Fig. 23.1 Scheme of a typical Swiss cement kiln ('dry process')

These materials are milled, sized, blended in a way designed to obtain a kiln feed with appropriate chemical and physical properties. The moisture is reduced to less than 1% before or during grinding. All cement plants in Switzerland use this type of technology ('dry process') as opposed to a raw material *slurry* ('wet process'). The dry raw mix is stored in silos until fed to the kiln.

The kiln transforms the raw mix into glass-hard clinker nodules, by a series of reactions which essentially comprise evaporation of residual water, calcination (decarboxylation of $CaCO_3$) and sintering of the remaining oxides at kiln temperatures close to 1500°C (so called pyroprocessing). Cement kilns are usually slightly inclined rotary kilns, where the raw mix is introduced at the elevated end and fuels are incinerated at the opposite end. The flow direction of the fuels and their subsequent exhaust gases is contrary to the flow direction of the raw materials/clinker product (see Fig. 23.1). The most common primary fuels to fire Swiss cement kilns are coal and some mineral oil, and only marginal amounts of natural gas. In 2004 the use of secondary fuels like slaughterhouse waste, waste oil, sewage sludge, waste solvents, plastic and rubber waste, accounted for over half the caloric input to Swiss cement kilns. In 2004, 39'840 tons of dried sewage sludge were incinerated in Swiss cement kilns (Cemsuisse 2005). Solid residues from fuels end up in the clinker output of the kiln. The latter is cooled to 90°C, mixed with gypsum, milled and packed.

The hot exhaust gases of the kiln are fed through a series of cyclone pre-heaters, which heat up the raw mix. The still hot gases exiting the pre-heaters are often used as a source of heat for drying raw materials in the raw material mill. Exhaust from the mill is filtered by fabric filters, and/or electrostatic precipitators (ESP's) and the collected solids are returned to the raw material input (so called 'combination mode' see Fig. 23.1). Because of this feedback loop, some pollutants may build up to large concentrations in the production process. Pollutants that are volatile enough to enter the kiln exhaust, but are retained in the filter ash will accumulate in the process. To prevent this, some filter ash is not returned to the raw material input, but mixed with the clinker product ('direct mode' see Fig. 23.1). Accumulations can also occur *within* the kiln, if elements evaporate in the hot end of the kiln, are transported by flue gas to the cooler part of the kiln, condense there into the solid phase, which moves in opposite direction of the flue gas, towards the hot end again. Chlorine is known to accumulate in this manner. To prevent this, some flue gas from the hot part of the kiln can be removed ('bypass mode' see Fig. 23.1). Some cement plants also include additional flue gas cleaners like scrubbers, activated charcoal filters, DeNOx facilities.

23.5.5 Allocation Choices

Allocation of energy production

Waste disposal processes which also generate energy are multi-functional processes: They provide the *service of waste disposal* and also generate useful energy. The question arises how much of the generated burden shall be allocated to energy products[64]. In this present bioenergy study, the focus of interest is the *energy utilisation function* of cement kilns. An allocation with an economical key is performed, and thus a portion of the generated burdens is allocated to the produced energy[65].

Carbon balance

In this present bioenergy study, specific guidelines for assessment of carbonaceous emissions like CO_2, CO, CH_4, VOC are presented (chapter 2.6). For the datasets regarding biomass incineration presented in this chapter, a part of the CO, CH_4, VOC emissions are allocated to the generated energy using an economical allocation key. However, in deviation of the given guidelines , no CO_2 uptake is inventoried in the energy datasets, which would be necessary to maintain a strict carbon balance. The resulting aberration in LCIA results is considered to be negligible. All biogenic CO_2 emissions from incineration are allocated to the *disposal function* and none to the utilised energy.

23.5.6 General Data Quality Considerations

In the ecoinvent database uncertainty values of LCI exchanges are often estimated using the Pedigree approach introduced in (Frischknecht et al. 2003a).

In this chapter exchanges in LCI raw data are often the result of a *chain of calculations*, which depend e.g. on the composition of the waste under consideration. For example, air emissions are derived from waste composition multiplied by transfer coefficients. Also, exchanges can be derived from *sums* of several contributions, e.g. transport services for a collection of materials. Likewise, the uncertainty information of these exchanges must be *calculated* along the chain of data flow and should not be given in a static or generic manner. The basic principles of these uncertainty calculations are described in part I of (Doka 2003).

The uncertainty of each element in a waste composition is estimated by a generic formula using the concentration *c* of that element. The geometric standard deviation (SDG_c) of that concentration is then given by the following expression:

$$SDG_c = N \cdot \ln(c) + 1 \qquad \text{with } N = -0.181$$

Similar formulas are applied for the uncertainty of transfer coefficients (see chapter 23.6.1 'Expenditures for the cement plant' on page 672). The Pedigree approach is applied on literature data used in the calculation of LCI exchanges. In most cases, uncertainty of exchanges will not be the direct result of a Pedigree approach, but a chain of calculations. Sources of uncertainty information are documented in the description of the according datasets.

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[64] The energy generated in a cement kiln is of course consumed internally by the clinkering process and not available as an external energy product. However, biomass waste incineration in cement kilns is able to replace fossil fuel inputs, which is the focus of interest of this process.

[65] In previous datasets different allocation choices were made. Burdens from waste incineration in cement production (secondary fuel) were fully allocated to the cement product and none to the waste disposal function (Althaus et al. 2004:27). Strictly speaking, the new datasets from this study are not compatible with previous datasets of the ecoinvent database, because the allocation choices are dissimilar.

Unit process inventories in this chapter are derived from allocation procedures. The applied allocation factors are to a certain degree uncertain (uncertainty in heating values and in energy gain, uncertainty of energy revenues). The ecoinvent database software does not allow input of uncertainty factors (SDG^2) concerning allocation factors. This uncertainty could be heeded alternatively in the uncertainty factors of the allocated exchanges, but this is currently not done in ecoinvent datasets. In this study the uncertainty of allocation factors are therefore neglected as well.

23.6 Life cycle inventory of raw sewage sludge incineration in cement kiln

In this life cycle inventory the incineration of undigested, raw sewage sludge in a Swiss cement kiln is presented. The same composition of wet raw sewage as in chapter 22 for municipal incineration is used (see Tab. 22.2 on page 630). Before incineration, the sewage sludge is first dewatered from 95% to 73% water content and then dried to 10% water content. Dewatering is assumed to occur in the wastewater treatment plant, prior to transport to the cement kiln, to reduce transport weight and costs. Drying is assumed to occur in the cement plant.

The system boundaries comprise dewatering of wet raw sludge, treatment of dewatering liquid, transport of dewatered sludge to cement kiln, drying of sludge, incineration in cement kiln. The expenditures in the cement kiln are included up to clinker production (kiln output). The further downstream burdens from the cement production, use and disposal are not heeded.

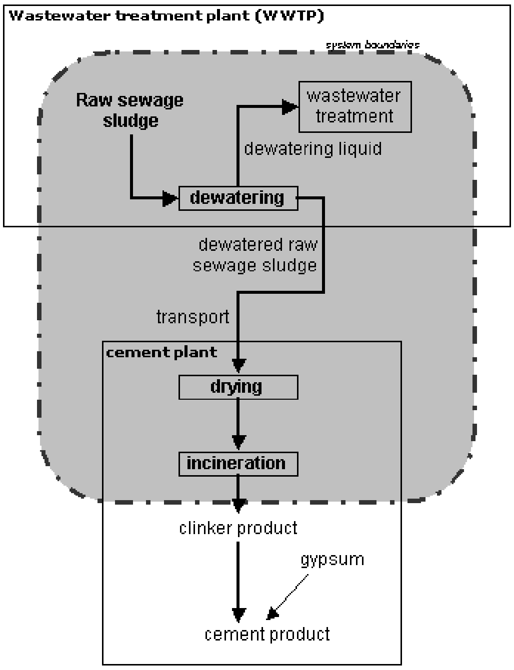

Fig. 23.2 System boundaries of raw sewage sludge incineration in cement kiln

The functional unit of the multi-output process 'raw sewage sludge, in cement plant' is 1 kilogram of wet raw sewage sludge with a water content of 95%. The generated unit process inventories are shown below.

Tab. 23.3 Datasets derived from the multi-output process ' raw sewage sludge, in cement plant '

Service function	Unit process dataset	Functional unit
disposal	disposal, raw sewage sludge, in cement plant, allocation price	1 kg wet sludge
utilised energy [1]	heat, raw sewage sludge, at cement plant, allocation price	1 MJ

1 The energy contained in the sludge is fully utilised internally for clinker production and is not available to external processes.

Sludge dewatering

Prior to incineration, the sludge is dewatered from 95% to 73% water content. The dewatering process is described qualitatively in chapter 22.5.2 'Sludge dewatering process description' on page 632. Dewatering is assumed to occur within the wastewater treatment plant. Dewatering is included in this inventory to have comparable system boundaries to biogas from sewage sludge digestion; see Spielmann (2007).

An average energy demand of several dewatering technologies of 0.0015 kWh electricity per kilogram wet sludge input is adopted from (Böhler et al. 2003). Most technologies also require the addition of flocculation agents to aggregate sludge particles. From (Böhler et al. 2003) the input of flocculation agents (quick lime, ferric chloride, polyelectrolyte) is adopted, see Tab. 22.14.

Tab. 23.4 Specific input of flocculation agents for dewatering process

Flocculation agent	**Specific input** (Böhler et al. 2003)		**This study** kg agent per kg wet sludge input
CaO	kg per m^3 input	7	**0.00233**
$FeCl_3$	kg per m^3 input	3.75	**0.00125**
Polyelectrolyte / polymer	kg per ton dry substance input	6.3	**0.0002625**

Approximately 820 grams of dewatering liquid are removed from the wet sludge by dewatering. This liquid is rich in ammonia, and is subsequently recycled into the wastewater treatment plant. The inventory of the disposal of dewatering liquid is calculated by application of the existing calculation tool for municipal wastewater treatment provided and described in (Doka 2003)[66]. The composition of dewatering liquid is shown in Tab. 22.15. The removal of these pollutants is heeded in the composition of the remaining dewatered sludge. It is assumed that composition of dewatering liquid is roughly the same for undigested and digested sewage sludge.

Tab. 23.5 Composition of dewatering liquid

Dewatering liquid composition		Siegrist 2006	Moser 2006	Fasel 2006	**This study**
Ammonia nitrogen (NH_4-N)	g/m^3	600 – 1000	500 – 800	984	**776.8**
Total organic carbon (TOC)	g/m^3			681	**681**
Soluble phosphorus (P_{sol})	g/m^3			16	**16**

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[66] In that tool, the full disposal chain of wastewater treatment is included by default (sewer transport, overload discharge, three-stage treatment in WWTP, sludge digestion and disposal of sludge). In order to assess the burdens created by internal treatment of dewatering liquid from digested sludge, only the burdens from 'three-stage treatment in WWTP' and 'sludge digestion' are heeded here, since the downstream fate of digested sludge is already being assessed. Overload discharge is set to zero.

Infrastructure for dewatering process

Data for the infrastructure of the dewatering process is approximated with infrastructure of a pump station used in drinking water supply (Althaus et al. 2004:803). A total uptake of 100 million tons of sludge input over the lifetime of the facility is assumed, resulting in a requirement of 10^{-11} units per kilogram wet sludge.

Transport to cement kiln

Over 900 WWT plants exist in Switzerland, but only 7 cement kilns. It is assumed that transport distances are on average 50 km. Transport per lorry 28t is assumed.

Sludge drying

Sludge drying is described qualitatively in chapter 23.5.3 'Sludge drying process description' on page 667. Drying reduces the water content of sludge to 10%. Literature values for energy consumption in sludge drying are reproduced in Tab. 23.6. The fuel demands *per kilogram input* range from 1.8 – 6.6 MJ/kg. This might be due to different technologies, different water contents in in- and outputs, resulting in dissimilar mass of removed water per kilogram input. The specific energy demand *per kilogram removed water* are shown in Tab. 23.6 on the right. These values show the same variability as the data per kilogram input. The arithmetic mean of the fuel consumption figures is used here, the specific electricity demand per kilogram removed water (from ERZ) is inventoried additionally.

Tab. 23.6 Energy consumption in sludge drying

Source	Water content in input w%	Water content in output w%	Energy carrier	Energy demand **MJ per kg input**	Specific energy demand **MJ per kg removed water**
Steil 2002	70%	10%	Fuel	3.036	4.555
Liebi 2002	–	–	Fuel	–	2.83
BUWAL 2004a	75%	8%	Fuel	1.8	2.47
ERZ [1]	70%	5%	Fuel	6.66	9.73
			Electricity	1.152	1.68
This study	73%	10%	Fuel	3.43	**4.9**
			Electricity	1.17 (0.327 kWh)	**1.68** (0.468 kWh)

1 Personal communication with Mr. Ch. Leitzinger, head of Materials and Energy Management of Entsorgung Recycling Zürich (ERZ, Zurich Municipal Waste Management Services), April 3, 2006.

The removed water is approximated to be unpolluted[67] and to be disposed in sewers.

Infrastructure of sludge drying is assumed to be covered already by inventoried expenditures from furnace and kiln infrastructure.

23.6.1 Expenditures for the cement plant

Sludge drying is described qualitatively in chapter 23.5.4 'Cement kiln incineration process description' on page 667. Expenditures for the cement plant are mainly taken from the inventory of clinker production provided by (Althaus et al. 2004). Unlike the other inventories of this chapter, the inven-

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[67] It is likely that a fraction of volatile pollutants like NH_3 or VOCs are removed during drying either in removed water or as air emissions. No data could be found to quantify these removals, but they are assumed to be small.

tory data of cement kiln incineration is not based on calculation tools already described in (Doka 2003). The calculation of the inventory data for cement kiln incineration is therefore presented here in a rather detailed manner.

The expenditures per kilogram clinker output given in the dataset 'clinker, at plant' are recalculated per megajoule fuel input[68] and then related to the energy input by the dried sludge only[69]. Direct air emissions are calculated *waste-specifically* based on the sludge composition (see 'Calculation of air emissions' on page 674). Other exchanges, like kiln infrastructure, energy and water consumption, auxiliary materials are not waste-specific, i.e. independent of waste composition. Input of activated coal is also inventoried independent of waste input, and based on the value of 0.00832 MJ coke per kg clinker given in (Althaus et al. 2003) and recalculated to 0.256 grams of coke per kg clinker based on a heating value of 32.5 MJ/kg.

Cement kiln flue gas purification technology

The air emissions of a cement kiln are strongly dependent on the applied flue gas cleaning technologies. For the purposes of this inventory it is important to know the flue gas cleaning technologies that are present in cement kilns *that incinerate sewage sludge*. The technology mix applied in the inventory should represent the technologies of sludge-burning cement kilns.

The results of (Liechti 2004) suggest that the cleaning technology with the most pronounced effect on emissions is the presence of an activated carbon filter. Activated carbon filters are rarely used in international cement kilns. The Swiss cement kiln in Siggenthal (owned by Holcim) is the only Swiss cement kiln that features an activated carbon filter (Seyler et al. 2005). The Siggenthal kiln is also one of the largest Swiss cement kilns. As shown in Tab. 23.7 Siggenthal takes up 38 w-% of all kiln-incinerated sludge. Thus 38 w-% of all sludge disposed in Swiss cement plants is incinerated in kilns featuring an activated carbon filter and 62 w-% in kilns without activated carbon filter (technology mix).

Tab. 23.7 Calculation of the national fraction of sewage sludge incinerated in Siggenthal cement plant.

	Parameter	unit	amount	source
A	Average annual production of clinker in Siggenthal plant (estimate)	t/a	520'000	Estimated from (HCB 1999, Holcim 2004)
B	Direct fuel input per kg clinker	MJ/kg	3.41	(Althaus et al. 2004)
C	Annual fuel consumption in Siggenthal plant	TJ/a	1'773.2	A* B / 10^6
D	Share of sewage sludge input in Siggenthal 2001 in relation to total fuel energy		7.5%	Holcim 2003
E	Annual sewage sludge input in Siggenthal plant	TJ/a	132.99	C*D
F	Heating value of dried sewage sludge	MJ/t	9700	Value used in cement industry. Personal communication of Daniel Kellenberger, EMPA, March 17, 2006.
G	Annual sewage sludge input in Siggenthal plant	t/a	13'710	E / F * 10^6
H	Annual sewage sludge input in all Swiss cement plants 2001	t/a	36'300	Estimated from (BUWAL 2001a, 2004b)
I	**National share of kiln-incinerated sewage sludge in Siggenthal plant**	w-%	**38%**	G / H

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[68] Using a direct fuel input of 3.42 MJ per kilogram clinker, calculated from data in (Althaus et al. 2004).

[69] The functional unit of 1 kilogram wet raw sludge will, after dewatering and drying, bring 0.85 MJ of heat to the cement kiln.

Calculation of air emissions

The direct emissions from dried sludge incineration are calculated according to the elemental composition of dried raw sludge (waste-specific emissions). For this calculation elemental transfer coefficients for cement kilns are used[70]. Data from (Liechti 2004) are used to derive transfer coefficients. Liechti (2004) presents a detailed substance-flow model of cement production, that calculates pollutant concentrations and flow intensities. Transfer coefficients are derived from this model for a technology mix of 38% *with* activated carbon filter and 62% *without* activated carbon filter[71]. Emissions of chromium to air are inventoried as 75% Cr^{III} and 25% Cr^{VI}, based on the inventory in (Althaus et al. 2004).

For some elements, no technology-specific but only generic transfer coefficients could be obtained. Transfer coefficients of sulfur are derived from data presented in (Döring 2004). Transfer coefficients for manganese are derived from the geometric mean of the values given in (BZL 2000:5). Transfer coefficients for phosphorus, silicon, calcium, iron, aluminium, and magnesium to air are estimated to be zero. The transfer coefficient for molybdenium is approximated with the value for manganese.

Nitrogen emissions in cement kiln are predominantly formed by oxidation of nitrogen in combustion air, due to the high flame temperatures of 2000°C ('thermal NO_x') (EPA 1994). It is assumed here that 99% of NO_x air emissions are caused by thermal NO_x, and are independent of the nitrogen content of the fuel. The remaining one percent is caused by oxidation of nitrogen in the fuel. Based on data presented in (Döring 2004) a transfer coefficient for fuel-N to NO_x–N of 4.8% is calculated.

Emissions of ammonia (from Althaus et al. 2004) and nitrous oxide (from Döring 2004) are assumed to be independent of the nitrogen content of the fuel. Emissions of dioxins, particulate matter, VOCs and carbon monoxide are assumed to be process-specific (i.e. independent of waste composition) and are adopted from (Althaus et al. 2004).

Tab. 23.8 Transfer coefficients to air for cement kiln

Element	Source	Generic cement kiln	With activated carbon filter	Without activated carbon filter	**This study [1]**
S	(Döring 2004)	5.04%			**5.04%**
N	(Döring 2004)	4.82%			**4.82%**
As	(Liechti 2004)		0.0000978%	0.0489%	**0.0304%**
Cd	(Liechti 2004)		0.0126%	6.03%	**3.74%**
Co	(Liechti 2004)		0.000134%	0.0668%	**0.0415%**
Cr	(Liechti 2004)		0.0000129%	0.00644%	**0.004%**
Cu	(Liechti 2004)		0.000271%	0.136%	**0.0842%**
Hg	(Liechti 2004)		2.89%	57.2%	**36.5%**
Mn	(BZL 2000:5)	0.00464%			**0.00464%**
Mo	Value for Mn				**0.00464%**
Ni	(Liechti 2004)		0.0000177%	0.00884%	**0.00549%**
Pb	(Liechti 2004)		0.00762%	3.71%	**2.3%**
Sb	(Liechti 2004)		0.0000845%	0.0422%	**0.0262%**
Sn	(Liechti 2004)		0.000297%	0.148%	**0.0919%**
Zn	(Liechti 2004)		0.0000852%	0.0426%	**0.0264%**

1 derived from a technology mix of 38% with activated carbon filter and 62% without activated carbon filter to heed the Swiss situation for kiln-incinerated sewage sludge.

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[70] Waste-specific emissions to air, for example for cadmium, are calculated by multiplying the cadmium content of dried sludge with the transfer coefficient of the cement kiln for cadmium to air. Air transfer coefficients essentially characterise how much of an input will be emitted to air and can range from 0% to 100%. Transfer coefficients are used throughout in (Doka 2003).

[71] Other parameters for the cement plant model of (Liechti 2004) were a share of 85% 'combination mode', 0% 'bypass mode' and the presence of ESP filters.

Pollutant transfer to cement product

The clinkering process is described here as a *multi-output process*. In other words, a cement kiln has not only the function to produce clinker for cement products but also the function of waste disposal. If this is so, then the *produced cement* can be thought of not only having *one* function as building product, but *also* as a 'disposal sink' for unwanted (ash) materials. Cement is then not only a building material commodity, but has at the same time a service function as a sink for pollutants.

Cement has exceptional properties that immobilise pollutants, however these properties are not eternal. Pollutants can partially leach from cement products during use phase. Ultimately, cement products will reach their end-of-life and be disposed of, for example in landfills. And if cement products are recycled, for example as secondary raw material in cement kilns, new air emissions are generated. Given enough time, parts of the heavy metals in cement can re-enter the biosphere by these routes and cause burdens.

If the cement has, as described above, not only one function (that of a building product), but at the same time the function of a pollutant sink, then a part of the pollutants released from cement products could be allocated to the disposal function of a cement kiln, and in turn to the disposal of sewage sludge. In other words, the process chain for the disposal of sewage sludge could be extend to the downstream life cycle of the cement product. The same would apply to other waste materials incinerated in cement kilns.

It could be interesting to estimate the downstream burdens of such 'disposal sinks' of cement commodities, and for example compare them to the more abundant waste sinks like landfills. However in ecoinvent, fate of pollutants in recycled materials are not attributed to the waste-producing (upstream) product life cycle. For recycling processes a system boundary cut-off is applied, if the recycled material can be assumed to have positive economic value[72]. For this inventory, the transformation of sludge (waste) into a valuable commodity (clinker) is assumed to occur after kiln incineration, i.e. when the sludge ashes leave the cement kiln in the clinker product. The system boundary cut-off is placed right after the cement kiln (cf. Fig. 23.2 on page 670).

Allocation

The inventoried exchanges are allocated according to the outline given in chapter 22.5.4 'General Allocation Choices' on page 633. Sludge incineration in cement kilns is a disposal route, but it also helps the production of clinker. By looking at revenues from disposal fees and avoided costs for fuel input, an allocation scheme can be drawn up and the expenditures in the cement kiln can be allocated.

Average production of 1 kg cement requires a fuel input of 2.85 MJ (Althaus et al. 2004)[73]. One kilogram of wet raw sewage sludge contains 5 w-% dry substance which, when dried and incinerated, will generate 0.85 MJ of heat (Michel 1938). As mentioned, the energy gain from sludge incineration is not a market product and therefore *no market price* is known for this particular product. Sludge incineration helps the kiln operators to reduce costs for commercial fuels. Therefore, an *inferred price* can be derived for sludge, which is – on a energetic basis – equal to the average costs for commercial fuels. In 2000, the average commercial fuels inputs in Swiss cement kilns were 1600 TJ/a oil and 5400 TJ/a coal, inducing costs of approximately 19.4 Mio. CHF/a (Cemsuisse 2005, Thomson 2005, Bachmann 2004). Thus, one megajoule of avoided commercial heat in Swiss cement kilns has a inferred value of 0.00277 CHF[74]. If one kilogram of wet raw sludge generates 0.85 MJ of heat, this equates to an inferred value of 0.00235 CHF. This is the revenue that can be attributed to the *energy supply function* of raw sludge incineration (energy assisting cement production).

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[72] On the other hand, waste materials are defined by a negative economic value, i.e. a disposal fee. Disposal of waste materials is attributed to the waste-producing process.

[73] Calculated from a fuel input of 3.42 MJ per kilogram clinker and a clinker content of 0.834 kg per kilogram generic cement (cement, unspecified).

[74] (19.4 Mio CHF) * 1'000'000 / (1600 + 5400 TJ) / 1'000'000

On the other hand, a *disposal fee* is required for sewage sludge incineration. Average Swiss sludge disposal fees charged for incineration in cement kilns in 2000 were 608 CHF per metric ton of sludge dry substance (BUWAL 2004a:24). The average disposal fee per functional unit (1 kilogram wet sludge with 5% dry substance content) is accordingly 0.03 CHF.

Tab. 23.9 Revenues generated from one kilogram of wet raw sewage sludge in cement kiln

	Disposal service	*Utilised heat*
Valued amounts [1]	1 kg	0.85 MJ
Fees and prices [1]	0.03 CHF/kg	0.00277 CHF/MJ heat
Generated revenues per kilogram wet raw sewage sludge	0.03 CHF	0.00235 CHF
Allocation keys for this dataset	**92.7% on disposal service**	**7.3% on energy utilisation**

1Sources see text above

All expenditures which are jointly used for sludge incineration (drying, electricity demand, infrastructure) are allocated. This resolves the question which portion of the expenditures in the jointly used cement kiln operation can be attributed to the kilns disposal function and its energy utilisation function, respectively. Also emissions from sludge incineration are allocated, except CO_2 which is allocated 100% to disposal (see section 'Carbon balance' on page 634). Expenditures that are solely used for cement production, but have no bearing on the sludge incineration (like gypsum addition to cement product, other raw material or fuel inputs) are not heeded in the inventory.

Data quality considerations

The general procedures to calculate uncertainty information used in the datasets of this chapter are described in 22.5.5 'General Data Quality Considerations' on page 634.

Uncertainty scores for waste-independent exchanges of the cement kiln, like infrastructure and processing energy, are adopted from (Althaus et al. 2004). Uncertainty of transports is recalculated based on the uncertainty of the heeded materials and the uncertainty of standard transport distances (Doka 2003).

Additional information about the MO-process 'raw sewage sludge, in cement plant', not already heeded in the calculation tools of (Doka 2003) or given in (Althaus et al. 2004) is displayed below.

Tab. 23.10 Uncertainty estimates for exchanges of the sludge drying process and additional air emissions from cement kiln

Exchanges	**Uncertainty factors** SDG[2] of a lognormal distribution	**Pedigree codes**	**Comment**
fuel + electricity demand for drying process	1.07	(1,3,1,1,1,1)	basic uncertainty of 1.05; Literature values from 4 sources
N_2O emissions in cement plant	1.51	(1,3,2,3,1,1)	basic uncertainty of 1.5;

The uncertainty of air emissions from cement kiln is the result of uncertainty of waste composition and the uncertainty of transfer coefficients to air. The latter is adopted from a generic formula for the uncertainty of transfer coefficients of municipal waste incinerators (Doka 2003). The geometric standard deviation (SDG_{TK}) of a transfer coefficient TK is given by the following expression:

$$SDG_{TK} = N \cdot \ln(TK) + 1 \qquad \text{with } N = -0.022$$

Tab. 23.11 Unit process raw data of 'raw sewage sludge, in cement plant. Not included in ecoinvent data v2.0

Explanation	401	InputGroup	OutputGroup	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	raw sewage sludge, in cement plant	disposal, raw sewage sludge, in cement plant, allocation price	heat, raw sewage sludge, at cement plant, allocation price	biogenic carbon content in elementary flow	biogenic carbon flow
	662			Location						CH	CH	CH		
	493			InfrastructureProcess						0	0	0		
	403			Unit						kg	kg	MJ	kg/kg	kg/f.u.
water, river			4	Ammonium, ion	-	water	river	0	kg	0.000275772	92.7	7.3		
			4	Nitrogen	-	water	river	0	kg	1.89298E-05	92.7	7.3		
air, high population density			4	NMVOC, non-methane volatile organic compounds, unspecified origir	-	air	high population density	0	kg	1.40188E-05	92.7	7.3		
			4	Carbon monoxide, biogenic	-	air	high population density	0	kg	0.000117285	92.7	7.3	42.9%	5.02649E-05
			4	Carbon dioxide, biogenic	-	air	high population density	0	kg	0.073280645	100.0	0.0	27.3%	0.019985631
			4	Methane, biogenic	-	air	high population density	0	kg	2.20799E-06	92.7	7.3	75.0%	1.65599E-06
			4	Sulfur dioxide	-	air	high population density	0	kg	9.38634E-05	92.7	7.3		
			4	Nitrogen oxides	-	air	high population density	0	kg	0.000601882	92.7	7.3		
			4	Dinitrogen monoxide	-	air	high population density	0	kg	4.03892E-06	92.7	7.3		
			4	Arsenic	-	air	high population density	0	kg	2.77647E-11	92.7	7.3		
			4	Cadmium	-	air	high population density	0	kg	2.43297E-09	92.7	7.3		
			4	Cobalt	-	air	high population density	0	kg	1.55439E-10	92.7	7.3		
			4	Chromium	-	air	high population density	0	kg	8.49172E-11	92.7	7.3		
			4	Copper	-	air	high population density	0	kg	1.09839E-08	92.7	7.3		
			4	Mercury	-	air	high population density	0	kg	2.37427E-08	92.7	7.3		
			4	Manganese	-	air	high population density	0	kg	5.69618E-10	92.7	7.3		
			4	Molybdenum	-	air	high population density	0	kg	1.02901E-11	92.7	7.3		
			4	Nickel	-	air	high population density	0	kg	6.69408E-11	92.7	7.3		
			4	Lead	-	air	high population density	0	kg	8.32491E-08	92.7	7.3		
			4	Tin	-	air	high population density	0	kg	8.54918E-10	92.7	7.3		
			4	Zinc	-	air	high population density	0	kg	9.38743E-09	92.7	7.3		
water, river			4	BOD5, Biological Oxygen Demand	-	water	river	0	kg	6.88474E-05	92.7	7.3		
			4	COD, Chemical Oxygen Demand	-	water	river	0	kg	0.00023236	92.7	7.3		
			4	TOC, Total Organic Carbon	-	water	river	0	kg	5.41197E-05	92.7	7.3	100.0%	5.41197E-05
			4	DOC, Dissolved Organic Carbon	-	water	river	0	kg	5.41197E-05	92.7	7.3		
			4	Sulfate	-	water	river	0	kg	5.4626E-05	92.7	7.3		
			4	Nitrate	-	water	river	0	kg	0.001251612	92.7	7.3		
			4	Phosphate	-	water	river	0	kg	1.41847E-05	92.7	7.3		
			4	Chloride	-	water	river	0	kg	5.69556E-05	92.7	7.3		
air, high population density			4	Heat, waste	-	air	high population density	0	MJ	1.197930304	92.7	7.3		
water, river			4	Heat, waste	-	water	river	0	MJ	0.009176202	92.7	7.3		
		5		quicklime, milled, packed, at plant	CH	construction materials	additives	0	kg	0.002333333	92.7	7.3		
		5		iron (III) chloride, 40% in H2O, at plant	CH	chemicals	inorganics	0	kg	0.001336866	92.7	7.3		
		5		chemicals organic, at plant	GLO	chemicals	organics	0	kg	0.0002625	92.7	7.3		
		5		transport, freight, rail	RER	transport systems	train	0	tkm	0.000350981	92.7	7.3		
		5		transport, lorry 28t	CH	transport systems	road	0	tkm	0.013531939	92.7	7.3		
		5		ammonia, liquid, at regional storehouse	CH	chemicals	inorganics	0	kg	0.000225648	92.7	7.3		
		5		electricity, low voltage, at grid	CH	electricity	supply mix	0	kWh	0.064231261	92.7	7.3		
		5		light fuel oil, burned in boiler 100kW, non-modulating	CH	oil	heating systems	0	MJ	0.614739745	92.7	7.3		
		5		iron sulphate, at plant	RER	metals	extraction	0	kg	6.35336E-05	92.7	7.3		
		5		aluminium sulphate, powder, at plant	RER	chemicals	inorganics	0	kg	1.7171E-05	92.7	7.3		
		5		disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05	92.7	7.3		
		5		disposal, paper, 11.2% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.27207E-05	92.7	7.3		
		5		sewer grid, class 3	CH	waste management	wastewater treatment	1	km	1.78765E-10	92.7	7.3		
		5		wastewater treatment plant, class 3	CH	waste management	wastewater treatment	1	unit	4.66825E-12	92.7	7.3		
technosphere		5		pump station	CH	water supply	production	1	unit	1E-11	92.7	7.3		
		5		treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	waste management	wastewater treatment	0	m3	0.000125516	92.7	7.3		
		5		electricity, medium voltage, at grid	CH	electricity	supply mix	0	kWh	0.014432115	92.7	7.3		
		5		diesel, burned in building machine	GLO	construction processes	machinery	0	MJ	0.003333361	92.7	7.3		
		5		Industrial machine, heavy, unspecified, at plant	RER	construction processes	machinery	1	kg	9.35719E-06	92.7	7.3		
resource		4		Water, unspecified natural origin	-	resource	in water	0	m3	6.76944E-07	92.7	7.3		
		4		Water, unspecified natural origin	-	resource	in water	0	m3	0.000402678	92.7	7.3		
technosphere		5		tap water, at user	RER	water supply	production	0	kg	0.084628552	92.7	7.3		
		5		disposal, inert waste, 5% water, to inert material landfill	CH	waste management	inert material landfill	0	kg	1.98918E-05	92.7	7.3		
		5		disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	waste management	municipal incineration	0	kg	1.11892E-05	92.7	7.3		
		5		refractory, basic, packed, at plant	DE	construction materials	bricks	0	kg	4.72779E-05	92.7	7.3		
		5		refractory, high aluminium oxide, packed, at plant	DE	construction materials	bricks	0	kg	3.41617E-05	92.7	7.3		
		5		refractory, fireclay, packed, at plant	DE	construction materials	bricks	0	kg	2.04065E-05	92.7	7.3		
		5		lubricating oil, at plant	RER	chemicals	organics	0	kg	1.1722E-05	92.7	7.3		
		5		chromium steel 18/8, at plant	RER	metals	extraction	0	kg	1.45637E-05	92.7	7.3		
		5		cement plant	CH	construction materials	others	1	unit	1.55953E-12	92.7	7.3		
		5		petroleum coke, at refinery	RER	oil	fuels	0	kg	6.36184E-05	92.7	7.3		
air, high population density			4	Particulates, > 10 um	-	air	high population density	0	kg	1.40722E-06	92.7	7.3		
			4	Particulates, < 2.5 um	-	air	high population density	0	kg	6.00415E-06	92.7	7.3		
			4	Particulates, > 2.5 um, and < 10um	-	air	high population density	0	kg	1.97011E-06	92.7	7.3		
			4	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	air	high population density	0	kg	2.38605E-13	92.7	7.3		
			4	Chromium VI	-	air	high population density	0	kg	2.83057E-11	92.7	7.3		
allocated products			2	disposal, raw sewage sludge, in cement plant, allocation price	CH	construction materials	concrete	0	kg	1	100.0	0.0	-2.0%	-0.020
			2	heat, raw sewage sludge, at cement plant, allocation price	CH	construction materials	concrete	0	MJ	0.8492	0.0	100.0	0.0%	0
Carbon Balance				Biogenic Carbon input					kg	0.000	0.000	0.000	totals	0.000
				Biogenic Carbon output in products					kg	-0.020	-0.020	0.000		-0.020
				Biogenic Carbon emissions, except CO2					kg	0.000	0.000	0.000		0.000
				Biogenic CO2 emissions					kg	0.020	0.020	0.000		0.020
				Carbon balance (inputs - outputs)						0.000	0.000	0.000		0.000

23.7 Cumulative results and interpretation

23.7.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please make your own calculations with this dataset, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

23.7.2 Raw sewage sludge in cement kiln

The multi-output process "raw sewage sludge, in cement plant" generates two unit processes. The dataset for disposal refers to one kilogram of wet sludge; the dataset for heat refers to one megajoule of utilised heat. Selected LCI results and the cumulative energy demand for these two unit processes are shown in Tab. 23.12.

The disposal of wet sewage sludge in cement kilns has a larger cumulated energy demand than the disposal of the same material in municipal waste incinerators (cf. inventories in Doka 2007). The main reason for this is that raw sewage is dewatered to a water content of 70% prior to municipal incineration, but dewatered and additionally dried to a water content of 10% prior to kiln incineration. The energy demand for drying is much larger than for mere dewatering.

Cement kilns have high incineration temperatures as opposed to municipal waste incinerators. One effect of this is larger amounts of nitrogen dioxide emissions, due to thermal NO_x formation. In Switzerland, cement kilns usually have lower occurrence of DeNOx stages in flue gas treatment than municipal waste incinerators, so the higher levels of thermal NOx formation are reflected in larger stack emissions of NO_x than municipal waste incinerators. Another effect of larger incineration temperatures is the low level of dioxin emissions, as opposed to municipal waste incinerators. This is due to destruction and/or prevention of formation of dioxins at higher temperatures.

Tab. 23.12 Selected LCI results and the cumulative energy demand for the unit processes generated from the multi-output process "raw sewage sludge, in cement plant". Calculation based on ecoinvent data v1.3

		Name		disposal, raw sewage sludge, in cement plant, allocation price	heat, raw sewage sludge, at cement plant, allocation price
		Location		CH	CH
		Unit	Unit	kg	MJ
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.94849	0.08745
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.50435	0.04650
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.15918	0.01468
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.00325	0.00030
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00554	0.00051
LCI results					
resource	Land occupation	total	m2a	0.0012561	0.0001158
air	Carbon dioxide, fossil	total	kg	0.0658633	0.0060727
air	NMVOC	total	kg	0.0000537	0.0000049
air	Nitrogen oxides	total	kg	0.0006528	0.0000602
air	Sulphur dioxide	total	kg	0.0001909	0.0000176
air	Particulates, < 2.5 um	total	kg	0.0000127	0.0000012
water	BOD	total	kg	0.0002364	0.0000218
soil	Cadmium	total	kg	3.745E-11	3.452E-12
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	0.0732654	-0.0000015
air	Methane, biogenic	total	kg	0.0000024	0.0000002
air	Carbon monoxide, biogenic	total	kg	0.0001095	0.0000101
	Heat, waste	total	MJ	2.329	0.215

The LCI results contain the sum totals of all exchanges of all sub-categories[75]. The entry "Carbon dioxide, biogenic, total" contains the *net total* of all emissions of biogenic CO_2 *minus* CO_2 uptake from air. The negative figure in the 2nd column probably originates from rounding mistakes or from biomass carbon emitted as VOC in background product life cycles.

Disposal of one kilogram wet raw sewage in a cement kiln consumes 4.4 MJ of primary energy. In contrast, the disposal in a current municipal waste incinerator consumes 0.2 MJ of primary energy, but produces no net energy (cf. inventories in Doka 2007). In the cement kiln 0.85 MJ heat is utilised. From an energy viewpoint, for cement kiln incineration 4.2 MJ *more* primary energy are consumed (mainly for sludge drying) to obtain 0.85 MJ of heat. This translates to a primary energy efficiency of 20%. This is low compared to conventional heat sources like fuel oil or coal with primary energy efficiencies of 70 – 80%. Whether the disposal of sewage sludge in cement kilns is *environmentally* preferable to disposal in municipal incinerators depends not only on the energy balance, but on the magnitude of emissions and other burdens produced in these processes.

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[75] For example, for air emissions the sum of all emissions to high population density air, low population density air, lower stratosphere + upper troposphere air, and unspecified air.

23.8 Conclusions

A multi-output dataset for the incineration of raw (i.e. undigested) sewage sludge in Swiss cement kilns is presented. This dataset is not included in ecoinvent data v2.0. The process inventory only refers to the expenditures necessary for sludge incineration, including dewatering and drying prior to incineration, but excludes expenditures that are needed for the actual cement production (cf. Fig. 23.2 on page 670).

The generated unit process for heat refers to the heat utilised in the cement plant. This heat is not available as a commercial product. The dataset is therefore similar to other industry-internal energy sources like "refinery gas, burned in furnace" for the petroleum industry or "natural gas, burned in gas turbine, for compressor station" for natural gas distribution.

Abbreviations

BUWAL	The Swiss Environmental Protection Agency (Bundesamt für Umwelt, Wald und Landschaft). Name change to BAFU (Bundesamt für Umwelt) in 2005.
ESP	Electrostatic precipitator. A type of filter in flue gas cleaning.
f.u.	functional unit (unit of measure that a unit process inventory relates to)
kWh	Kilowatt-hour (1000 Watt hours)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule (1'000'000 joules)
SDG	(also SDg or GSD) geometric standard deviation. Measure of uncertainty, cf. (Frischknecht et al. 2003)
WWT	(municipal) wastewater treatment
WWTP	(municipal) wastewater treatment plant. Also called effluent treatment plant or sewage treatment plant (German: 'Kläranlage', Swiss German: 'Abwasser-Reinigungs-Anlage, ARA').

Glossary of terms

Raw sludge	(Ger. 'Rohschlamm', 'Frischschlamm') Sludge from the wastewater treatment prior to anaerobic digestion. See also digested sludge.
Digested sludge	(Ger. 'Faulschlamm', 'Gärschlamm') Sludge from the wastewater treatment after anaerobic digestion/biogas production. See also raw sludge.
Sewage	Input to the WWTP, transported in sewers. Identical to 'wastewater'. The output of the WWTP is called 'effluent' or 'discharge'.

Appendices: EcoSpold Meta Information

Tab. A. 53 EcoSpold Meta Information of 'raw sewage sludge, in cement plant '

Type	**Field name, IndexNumber**	
ReferenceFunction	Name	raw sewage sludge, in cement plant
Geography	Location	CH
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	5
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	43
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	dewatering of sludge. treatment of dewatering liquid. transport of dewatered sludge to cement kiln incinerator. drying of sludge. waste-specific air and emisions from kiln incineration, auxiliary material consumption and transport. Process energy demands.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Klärfrischschlamm, in Zementwerk
ReferenceFunction	Synonyms	Unvergärter Rohschlamm der Kläranlage//unfermented sewage sludge
ReferenceFunction	GeneralComment	Incinerated amount = 0.0538kg. Incinerated waste contains 100% raw sewage sludge, 10% water; . waste composition (wet, in ppm): upper heating value 16.92 MJ/kg; lower heating value 15.79 MJ/kg; H2O 100000; O 203660; H 46286; C 370290; S 17305; N 39423; P 18712; B n.a.; Cl n.a.; Br n.a.; F n.a.; I n.a.; Ag n.a.; As 1.6997; Ba n.a.; Cd 1.208; Co 6.9635; Cr 52.653; Cu 242.37; Hg 1.208; Mn 228.14; Mo 4.1213; Ni 22.667; Pb 67.149; Sb n.a.; Se n.a.; Sn 17.285; V n.a.; Zn 660.33; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 25685; Fe 115990; Ca 43585; Al 12875; K n.a.; Mg 4893.2; Na n.a.; Share of carbon in waste that is biogenic 100%.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	construction materials
ReferenceFunction	SubCategory	concrete
ReferenceFunction	LocalCategory	Mineralische Baustoffe
ReferenceFunction	LocalSubCategory	Beton und Betonwaren
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	1997
TimePeriod	EndDate	2001
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	
Geography	Text	Based on data from Switzerland and Germany.
Technology	Text	Dry process cement kiln as used in Switzerland. Flue gas cleaning technology mix with 38% activated carbon filter representing the fate of kiln-incineratd sludge in Switzerland early 2000s.
Representativeness	Percent	
Representativeness	ProductionVolume	
Representativeness	SamplingProcedure	waste-specific calculation based on literature data
Representativeness	Extrapolations	
Representativeness	UncertaintyAdjustments	uncertainty of waste input composition data derived from generic formula GSD(c) = N*ln(c)+1
DataGeneratorAndPublication	Person	46
DataGeneratorAndPublication	DataPublishedIn	2
DataGeneratorAndPublication	ReferenceToPublishedSource	16
DataGeneratorAndPublication	Copyright	1
DataGeneratorAndPublication	AccessRestrictedTo	0
DataGeneratorAndPublication	CompanyCode	
DataGeneratorAndPublication	CountryCode	
DataGeneratorAndPublication	PageNumbers	
ProofReading	Validator	43
ProofReading	Details	automatic validation in Excel
ProofReading	OtherDetails	none

References

Althaus et al. 2004	Althaus H.-J., Chudacoff M., Hellweg S., Hischier R., Jungbluth N., Osses M. Primas A. (2004) Life cycle inventories of chemicals. ecoinvent report No. 8. Swiss Centre for Life Cycle Inventories, Duebendorf, 2004
Böhler et al. 2003	Böhler M., Siegrist H., Pinnow D., Müller D., Krauss W., Brauchli H. (2003) Neue Presstechnologie zur verbesserten Klärschlammentwässerung Schlussbericht zu den Untersuchungen auf der ARA Glarnerland (AVG) . EAWAG Swiss Federal Institute for Environmental Science and Technology, Dübendorf, Switzerland. Retrieved March 16, 2006 from http://www.bucherguyer.ch/foodtech/klaerschlammentwaesserung__bucher_presse_d-4.pdf
BUWAL 2001a	BUWAL (2001) Entsorgung des Klärschlammms 2000, Stand 11.12.2001, BUWAL, Berne, Switzerland. Retrieved March 2, 2002 from http://www.buwal.ch/abfall/docu/pdf/tab15_d.pdf
BUWAL 2004a	Laube A., Vonplon A. (2004) Klärschlammentsorgung in der Schweiz – Mengen- und Kapazitätserhebung. Umwelt-Materialien Nr. 181, BUWAL, Berne, Switzerland. Retrieved April 21, 2006 from http://www.umwelt-schweiz.ch/imperia/md/content/abfall/ks_bericht_d.pdf
BUWAL 2004b	BUWAL (2004) Entsorgung des Klärschlammms 2002, Stand 7.8.2004, BUWAL, Berne, Switzerland. Retrieved June 5, 2005 from http://www.umwelt-schweiz.ch/imperia/md/content/abfall/tab17-02_d.pdf
BZL 2000	BZL, Deutsche Projekt Union DPU (2000) Anforderungen an Ersatzbrennstoffe aus Abfällen für die Zementindustrie Oyten, Köln. Retrieved March 4, 2002 from http://www.uvm.baden-wuerttemberg.de/uvm/abt2/zement/EBS_Zem_250900_end.pdf
Cemsuisse 2005	cemsuisse (2005) Kennzahlen 2004. Verband der Schweizerischen Cementindustrie, Berne. Retrieved March 16, 2006 from http://www.cemsuisse.ch/file/Kennzahlen_04_d_f.pdf
Doka 2003	Doka G. (2003) Life Cycle Inventories of Waste Treatment Services. Final report ecoinvent 2000 No. 13. EMPA St. Gallen, Swiss Centre for Life Cycle Invento-ries, Dübendorf, CH
Doka 2007	Doka G. (2007) 1 Incineration of Biowaste and Sewage Sludge. Chapter of Jungbluth N., Chudacoff M., Dauriat A., Dinkel F., Faist Emmenegger M., Gnansounou E., Kljun N., Spielmann M., Stettler C., Sutter J. (2007) Life Cycle Inventories of Bioenergy. Final report, ESU-services, Uster, CH.
Döring 2004	Döring U. (2004) Zement (Prozessfeuerung) (Inventory data for for various fuels in cement kiln) Inventroy database Probas (Prozessorientierte Basisdaten für Umweltmanagement-Instrumente), Umweltbundesamt. Berlin. Retrieved March 16, 2006 from http://www.umweltbundesamt.de/uba-info-daten/daten/baum/php/sektoren.php?&prozessid={4576C918-4979-40EF-BF73-65F7E3C7DC76}&id=1705217&sid=3
Bachmann 2004	Bachmann R. (2004) Fossil-thermische Kraftwerke. Vortrag für Bundesamt für Energie. Energy Consulting Group Retrieved July 17, 2006 from http://www.bfe.admin.ch/php/modules/pubikationen/stream.php?extlang=de&name=de_181145028.pdf
EPA 1994	U.S. Environmental Protection Agency (1994) Alternative Control Techniques Document – NOx Emissions From Cement Manufacturing. EPA-453/R-94-004, U.S. Environmental Protection Agency, Emission Standards Division, Office Of Air Quality Planning And Standards, Research Triangle Park, North Carolina. Retrieved April 6, 2006 from http://epa.gov/ttn/catc/dir1/cement.pdf

Fasel 2006	Fasel A. (2006) Technischer Bericht 2005. ARA Region Bern AG, Berne. Retrieved March 26, 2006 from http://www.ara-bern.ch/d/pdf/tech_bericht_01.pdf
Frischknecht et al. 2004a	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2004a) Overview and Methodology. Final report ecoinvent 2000 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
Frischknecht et al. 2004c	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004c) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.
HCB 1999	HCB (1999) Umweltschutz in der Baustoffproduktion: Ziele, Massnahmen, Erfolge – Umweltbericht HCB "Holderbank" Cement und Beton mit den Daten der Jahre 1996 bis 1998. Herausgeber: HCB "Holderbank" Cement und Beton. Retrieved March 16, 2006 from http://www.holcim.ch/Upload/CH/Publications/de_media_press_publications_umweltbericht_1.pdf
Holcim 2001	Holcim (2001) Zement und Umwelt: eine nachhaltige Bindung. Holcim (Schweiz) AG (large Swiss cement manufacturer). Retrieved March 16, 2006 from http://www.holcim.ch/Upload/CH/Publications/Holcim_Edition01_D.pdf
Holcim 2003	Holcim (2003) Siggenthal: alternative Stoffe / geplante Umweltmassnahmen. Holcim (Schweiz) AG (large Swiss cement manufacturer). Retrieved April 16, 2004 from http://www.holcim.com/CH/DE/b/XXX/oid/536889585/module/gnm50/jsp/templates/editorial/editorial.html
Holcim 2004	Holcim (2004) Kennzahlen Zementwerk Siggenthal 2002. Holcim Switzerland. Retrieved March 15, 2006 from http://www.holcim.com/CH/EN/b/XXX/oid/536889516/module/gnm0/jsp/templates/editorial/editorial.html
Liebi 2002	Liebi C. (2002) Umweltbericht 2001 Kläranlage Kloten/Opfikon. Glattbrugg, Switzerland. Retrieved December 28, 2002 from http://www.klaeranlage.ch/download/Umweltbericht%202001.pdf
Liechti 2004	Liechti J. (2004) Revidiertes Stofflussmodell des Zementofensystems. NEOSYS AG Umweltschutz und Wärmetechnik, Gerlafingen, contracted by Revisionskommission Abfallverwertung im Zementwerk.
Michel 1938	Michel R. (1938) Berechnung der Verbrennungswärmen fester und flüssiger Brennstoffe nach den Wärmewerten ihrer Einzelbestandteile. Feuerungstechnik 26, No.9, p.273-278 (Leipzig, Germany. Appeared 1912 –1943).
Moser 2006	Moser R. (2006) Zustand der Abwasserreinigungsanlagen in der Schweiz: Handlungsbedarf. Gebr. Hunziker AG, Winterthur. Im Rahmen der Fachveranstaltung 'Instandsetzung von Abwasserreinigungsanlagen und begehbaren Kanälen. 30 März 2006' Bau und Wissen Nr. 854572, Wildegg. Retrieved April 3, 2006 from http://www.hunzikerwater.ch/downloads/854571%20Referat.pdf
Seyler et al. 2005	Seyler C., Hellweg S., Monteil M. and Hungerbühler K. (2005) Life Cycle Inventory for Use of Waste Solvent as Fuel Substitute in the Cement Industry - A Multi- Input Allocation Model. In: Int J LCA, 10 (2), pp. 120-130.
Siegrist 2006	Siegrist H. (2006) Biological treatment of high strength ammonia waste waters. Eawag Environmental Engineering, Duebendorf, Switzerland. Retrieved March 26, 2006 from http://www.eawag.ch/research_e/ing/VT_proc_engineering/fux/e_faulwasser.htm

Spielmann 2007	Spielmann M. (2007) Biogas. Chapter of Jungbluth N., Chudacoff M., Dauriat A., Dinkel F., Faist Emmenegger M., Gnansounou E., Kljun N., Spielmann M., Stettler C., Sutter J. (2007) Life Cycle Inventories of Bioenergy. Final report, ESU-services, Uster, CH.
Steil 2002	Steil R. (2002) Ausgewählte Stoffstrombilanzen für verschiedene Szenarien der Verwertung der luxemburger Klärschlämme. Lycée Technique Esch (LTE), Esch-sur-Alzette. Retrieved March 21, 2006 from http://www.crte.lu/mmp/online/website/content/water/76/203/file_1309/crte-2002-klaerschlammverwertung.pdf
Thomson 2005	Thomson Datastream. Fuel prices 1995-2005. Cited in Tor S. (2005) Energierohstoff mit Zukunft: Kohle. Bank Coop. Retrieved March 17, 2006 from http://www.bankcoop.ch/pulsletter-14-2005.pdf

Part II

II.vi. Chemicals

Authors: see individual chapter

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24 Allyl chloride, hydrochloric acid, 36%, in water, and dichloropropene, from reacting chlorine and propylene

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24.1 Introduction

Allylic chloride (CH_2=CH-CH_2Cl, CAS-No. 107-05-1) is a chlorinated organic chemical that is mostly used as an intermediate for epichlorohydrin manufacture. Synonyms for allyl chloride: allylic chloride, 3-chloropropene, 3-chloro-1-propene.

Hydrogen chloride (HCl), CAS 7647-01-0 is a colourless to yellowish fuming liquid with a sharp, pungent odor. It is a strong highly corrosive acid. HCl is soluble in water and alcohol but is not soluble in hydrocarbons. HCl has a molecular weight of 36.45 and boils at 85°C**.**

1,3-dichloropropene ($C_3H_4Cl_2$), CAS 542-75-6, is a mixture of trans- and cis isomers. Both isomers have their own CAS numbers. They are colourless liquids (cis isomer can tend toward amber) and are flammable. The trans isomer has a boiling point of 112 °C, the cis isomer boils at 104 °C. Both isomers are eye, skin and respiratory irritants (aka tear gas).

The information on allyl chloride in ecoinvent v 1.2 has been partially revised with regard to the coproducts, chemical and physical properties, and 11.6 ff.

24.2 Reserves and Resources of Allyl Chloride

Allyl chloride is a chlorinated organic chemical that is produced from the chlorination of propylene. From the worldwide production in the order of 850 kt in 1997, more than 90% – about 800 kt – were used for the production of epichlorhydrin, and only the remaining rest was used for other applications [Krähling et al, 2000].

24.3 Characterisation of Allyl Chloride

Allyl chloride is at room temperature a colourless, mobile liquid that has a penetrating, pungent odour. It is a highly toxic chemical if inhaled, swallowed or absorbed through the skin. Inhalation may be fatal. Allyl chloride is a confirmed animal carcinogen. (MSDS allyl chloride).

Tab. 24.1 Chemical and physical properties of allyl chloride, hydrochloric acid und 1,3-dichloropropene

Property	**Allyl chloride**	**Hydrochloric acid**	**1,3-dichloropropene**	**Unit**	**Remarks**
Molecular weight	76.53 [1]	36.45 [3]	110.9 [4]	g mol^{-1}	
Specific gravity	0.939 [2]	1.19 [3]	1.2 [4]	g cm^{-3}	at 20° C
Boiling point	-134 [1]	109 [3]	108 [4]	° C	at normal pressure
Melting point	44.4 [1]	- 25 [3]	n.g.	° C	at normal pressure
Carbon content	0.47	0	0.324	kg kg^{-1}	
Hydrogen content	0.065	0.027	0.036	kg kg^{-1}	
Chlorine content	0.464	0.973	0.64	kg kg^{-1}	

1 Source: [Krähling at al, 2000]

2 MSDS Allyl chloride, 2003

3 http://ptcl.chem.ox.ac.uk/MSDS/HY/hydrochloric_acid.html

4 http://www.chemexper.com

24.4 Use of the Product

According to [Krähling et al, 2000], the most important use of allylic chloride is its function as an intermediate in the production of epichlorhydrin. Besides this, allylic chloride is also a starting material for the production of a variety of different chemicals – e.g. glycerol, esters like phthalic or carboxylic acids or allyl ethers.

Most of the produced HCl directly enters into other processes, and of that relatively little is actually sold on the market. More information may be found in the corresponding ecoinvent chapter on HCl.

The dichloropropene isomer mix is a high volume chemical with production exceeding 1 million pounds annually in the U.S. It is primarily used as a soil fumigant (pesticide).

24.5 System Characterisation

According to [Krähling et al., 2000], liquid propene is vaporized and preheated to 350 – 400°C. Then this gas is feed into the reactor together with gaseous chlorine. There, at about optimal conditions, chlorine reacts completely. Following to the reaction chamber are a serie of distillation steps, aiming in separating the product (allylic chloride) from unreacted substances and the in parallel synthesised by-products (mainly dichlorides like 1,2-dichloropropane and hydrogen chloride). The first step – called prefractionator – removes gaseous hydrogen chloride as well as unreacted substances (propene). In the further distillation steps the different by-products are separated from allylic chloride. The removed gaseous mixture is separated into liquid hydrogen chloride (by adding water) and propene. The latter one is washed with sodium hydroxide and then re-liquified and goes back to the beginning of the process scheme.

Net Reaction (Overcash 1998 - 2004)

$CH_2=CH-CH_3$ + Cl_2 → $CH_2=CH-CH_2Cl$ + HCl

Propylene **Chlorine** **Allyl Chloride** **Hydrogen Chloride**

A typical process flow scheme for the production of allyl chloride is shown in Fig. 24.1.

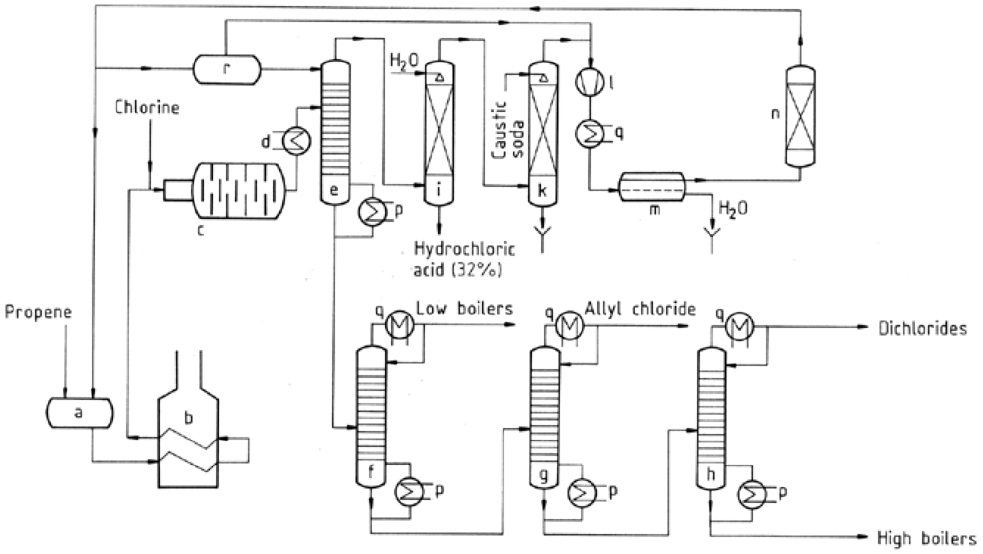

Fig. 24.1 Process chain for the production of allylic chloride (Fig.1 out of [Krähling et al., 2000] – showing liquid propene storage [a], evaporator [b], the actual reactor [c], cooler [d], the different distillation steps [e] - [h], flue gas cleaning equipement [i] – [n])

24.6 Life Cycle Inventories (Overcash 1998 – 2004)

24.6.1 Raw materials and auxiliaries

Allyl chloride is produced from propylene and chlorine. The input values are shown in Tab. 24.2.

Tab. 24.2 Consumption of raw materials for the production of 1 metric ton allyl chloride

Input	Overcash 1998-2004
Chlorine (kg)	1189
Propylene (kg)	679
Process Water (kg)	1085

24.6.2 Energy

Overcash 1998 – 2004 reports a net energy input of 2.22 MJ/kg (does not include recovered energy) and an electricity input of 0.127 kWh per kg of allyl chloride.

Tab. 24.3 Energy consumption for the production of 1 kg allyl chloride

Input	**Overcash 1998 - 2004**
Steam (MJ)	2.22
Electricity (kWh)	0.127

24.6.3 Emissions to air

It is assumed that 100 % of the electricity consumed, i.e. 458.2 kJ/kg allyl chloride is converted to waste heat and that 100 % of the waste heat is released to the air.

Tab. 24.4 Process emissions to air from the production of 1 kg allyl chloride

Output	
Waste heat (kJ)[1]	458.2
Allyl Chloride (g) [2]	2.04
Propylene (g) [2]	3.4
HCl (g) [2]	3.03
Chlorine (g) [2]	5.94

1 Source: calculated from electricity input

2 Source: Overcash 1998 - 2004, pre-treatment values! It is asumed that the emissions are incinerated, according to IPPC Chemicals, 2002. The stack gases are treated with an alkali liquor, producing calcium and sodium hypochlorite, again according to IPPC Chemicals, 2002, p.60. Some plants completely incinerate the waste gases and avoid wastewatwer generation. It is assumed that the inventory “disposal, solvents mixture, 16.5% water, to hazardous waste incineration” is a sufficient approximation.

24.6.4 Emissions to water

IPPC Chemicals, 2002 reports post-treatment values for the water emissions from allyl chloride manufacture. The values of table 3.17 of that report are given in Tab. 24.5.

Tab. 24.5 Process emissions to water from the production of 1 kg allyl chloride

Output	
AOX (g)[1]	0.15
COD (g)[1]	3.5
BOD (g)[2]	3.5
DOC (g)[2]	1.3

1 Source: IPPC Chemicals, 2002

2 calculated from 1

24.6.5 Infrastructure and land use

No information was readily available about infrastructure and land-use of allyl chloride plants. Therefore, in this study, the infrastructure is estimated based on the inventory "chemical plant, organics". This inventory assumes a built area of about 4.2 ha, an average output of 50'000 t/a, and plant life of fifty years. For this study, the estimated value is 4.00 E-10 units per kg of produced chemical.

24.7 Allocation of co-products

Within the production of allyl chloride two by-products that are sold on the market are also produced..

The yields of these co-products are given in Tab. 24.7.

As an allocation factor the weight of the product multiplied by its bulk shipping price (where available) was used. The used allocation factors are also given in Tab. 24.5.

Tab. 24.6 Allocation of allyl chloride and co-products

Process	**Reaction of gaseous propylene with chlorine**			
	Unit	**Mass**	**Bulk price ($/lb)**	**Allocation factor**
Allyl chloride, from reacting propylene and chlorine, at plant, RER	kg	1000	0.98	86.18%
Hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant, RER	kg	1666.8	0.033	4.84%
Dichloropropene, from reacting propylene and chlorine, at plant	kg	113.02	0.904	8.98%

24.8 Overview of input/output data and data quality considerations

The following table summarizes the input and out put data as well as the uncertainties used for the production of allyl chloride.

Tab. 24.7 Overview of input/output data and quality considerations for the manufacture of allyl chloride, dichloroprpene and hydrochloric acid, 36% from the reaction of chlorine with propylene

Input Category	Output Category	Name	Location	Category	Sub Category	Infra-structure Process	Unit	reaction of propylene and chlorine	Uncertainty Type	Standard Deviation 95%	General Comment	allylic chloride, at plant	dichloropropene, from reacting propylene and chlorine, at plant	hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant
		Location						RER				RER	RER	RER
		Infrastructure Process						0				No	No	No
		Unit						kg				kg	kg	kg
5	-	chlorine, liquid, production mix, at plant	RER	-	-	No	kg	1.19E+00	1	1.08	(2,2,1,3,1,1); literature	86	9	5
5	-	chemical plant, organics	RER	-	-	Yes	unit	4E-10	1	1.30	(4,5,na,na,na,na); infrastructure of a typical plant	86	9	5
5	-	electricity, medium voltage, production UCTE, at grid	UCTE	-	-	No	kWh	0.13	1	1.08	(2,2,1,3,1,1); literature	86	9	5
5	-	heat, unspecific, in chemical plant	RER	-	-	No	MJ	2.2	1	1.08	(2,2,1,3,1,1); industry source	86	9	5
5	-	propylene, at plant	RER	-	-	No	kg	0.679	1	1.08	(2,2,1,3,1,1); literature	86	9	5
5	-	transport, freight, rail	RER	-	-	No	tkm	0.9	1	1.30	(4,5,na,na,na,na); standard rail transport distance	86	9	5
5		disposal, solvents mixture, 16.5% water, to hazardous waste incineration	CH			No	kg	0.014	1	1.21	(4,2,1,3,1,1); approximation	86	9	5
5	-	transport, lorry 32t	RER	-	-	No	tkm	0.1502	1	1.30	(4,5,na,na,na,na); standard trucking distance	86	9	5
5	-	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	-	-	No	m3	0.0000035	1	1.21	(4,2,1,3,1,1); approximation	86	9	5
5	-	water, completely softened, at plant	RER	-	-	No	kg	1.085	1	1.08	(2,2,1,3,1,1); literature	86	9	5
-	4	AOX, Adsorbable Organic Halogen as Cl	-	water	river	-	kg	0.00015	1	1.21	(4,2,1,3,1,1); calculation	86	9	5
-	4	BOD5, Biological Oxygen Demand	-	water	river	-	kg	0.0035		1.21	(4,2,1,3,1,1); calculation	86	9	5
-	4	COD, Chemical Oxygen Demand	-	water	river	-	kg	0.0035	1	1.21	(4,2,1,3,1,1); calculation	86	9	5
-	4	DOC, Dissolved Organic Carbon	-	water	river	-	kg	0.0013		1.21	(4,2,1,3,1,1); calculation	86	9	5
-	4	Heat, waste	-	air	high population	-	MJ	0.46	1	1.21	(4,2,1,3,1,1); estimated	86	9	5
-	4	TOC, Total Organic Carbon	-	water	river	-	kg	0.0013		1.21	(4,2,1,3,1,1); estimated	86	9	5
-	2	allylic chloride, at plant	RER	-	-	No	kg	1				100	0	0
-	2	dichloropropene, from reacting propylene and chlorine, at plant	RER	-	-	No	kg	0.113				0	100	0
-	2	hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant	RER	-	-	No	kg	1.67				0	0	100

24.9 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 24.8 shows selected LCI results and the cumulative energy demand for the production of allylic chloride and its coproducts.

Tab. 24.8 Selected LCI results and the cumulative energy demand for the production of allylic chloride and coproducts

		Name		allylic chloride, at plant	dichloropropene, from reacting propylene and chlorine, at plant	hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant
		Location		RER	RER	RER
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	55.4	51.3	1.9
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	10.2	9.5	0.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.6	1.5	0.1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.3	0.2	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.5	0.4	0.0
LCI results						
resource	Land occupation	total	m2a	9.6E-2	8.9E-2	3.3E-3
air	Carbon dioxide, fossil	total	kg	2.0E+0	1.8E+0	6.8E-2
air	NMVOC	total	kg	1.3E-3	1.2E-3	4.7E-5
air	Nitrogen oxides	total	kg	6.0E-3	5.6E-3	2.1E-4
air	Sulphur dioxide	total	kg	7.5E-3	6.9E-3	2.6E-4
air	Particulates, < 2.5 um	total	kg	4.3E-4	3.9E-4	1.5E-5
water	BOD	total	kg	4.6E-3	4.2E-3	1.6E-4
soil	Cadmium	total	kg	2.0E-9	1.9E-9	7.1E-11

The cumulative energy demand for both allylic chloride and its coproduct dichloropropene are typical for chlorinated hydrocarbons. The emission levels for both compounds are remarkably similar, which stems from the fact that the energy demand is similar. The coproduct hydrogen chloride is discussed below.

24.9.1 Hydrogen chloride

Tab. 24.9 shows selected LCI results and the cumulative energy demand for the production of hydrogen chloride from allylic chloride production and hydrogen chloride from a mix of production pathways.

Tab. 24.9 Selected LCI results and the cumulative energy demand for hydrochloric acid, 36%, as a coproduct of allylic chloride production, and hydrochloric acid, 30%, from an assumed average

		Name		hydrochloric acid, 36% in H2O, from reacting propylene and chlorine, at plant	hydrochloric acid, 30% in H2O, at plant
		Location		RER	RER
		Unit	Unit	kg	kg
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.9	10.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.4	5.9
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.1	0.9
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.2
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.0	0.3
LCI results					
resource	Land occupation	total	m2a	3.3E-3	7.5E-2
air	Carbon dioxide, fossil	total	kg	6.8E-2	7.5E-1
air	NMVOC	total	kg	4.7E-5	2.8E-4
air	Nitrogen oxides	total	kg	2.1E-4	1.6E-3
air	Sulphur dioxide	total	kg	2.6E-4	3.0E-3
air	Particulates, < 2.5 um	total	kg	1.5E-5	2.2E-4
water	BOD	total	kg	1.6E-4	9.8E-4
soil	Cadmium	total	kg	7.1E-11	1.6E-9

Hydrochloric acid from reacting propylene and chlorine complements the already existing inventory hydrochloric acid at plant in ecoinvent. A comparison of the two inventories shows that one major difference lies in the total energy usage. This stems from the fact this chapter's HCl is the result of an allocation in a specific process, and the already existing inventory combines the pathway "combustion of chlorine with hydrogen" with the sodium sulfate pathway, due to a lack of representative data.

Appendix: EcoSpold Meta Information

Name	reaction of propylene and chlorine
Location	RER
InfrastructureProcess	0
Unit	kg
Type	5
Version	1.0
energyValues	0
LanguageCode	en
LocalLanguageCode	de
Person	13
QualityNetwork	1
DataSetRelatesToProduct	1
IncludedProcesses	Multi-output process that produces three outputs: allyl chloride, hydrochloric acid (36wt%) and 1,3-dichloropropene.
Amount	1
LocalName	Reaktion von Propylen mit Chlor
Synonyms	
GeneralComment	Liquid propene is reacted with gaseous chlorine
InfrastructureIncluded	
Category	chemicals
SubCategory	organics
LocalCategory	Chemikalien
LocalSubCategory	Organisch
Formula	
StatisticalClassification	
CASNumber	
StartDate	1998
EndDate	2004
DataValidForEntirePeriod	1
OtherPeriodText	
Text	RER
Text	based on industry data in the US

References

Wells, 1999	G. Margaret Wells, "Handbook of Petrochemicals and Processes", 2nd edition, Ashgate, 1999
IPPC Chemicals, 2002	European Commission, Directorate General, Joint Research Center, "Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry", February 2002
MSDS Allyl Chloride	Material Safety Data Sheet, Allyl Chloride, Version 12, Resolution Performance Products, 09/09/2003

Overcash, 1998 - 2004	Overcash, M., Chemical life cycle database, Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27695-7905
Krähling et al., 2000	Krähling L., Krey, J., and Jakobsen, G.(2000). Allyl compounds. In: Ullmann's Encyclopedia of Industrial Chemistry, sixth edition, 2003 electronic release, 6th electronic release edition. Wiley Interscience New York, Online version under: www.mrw.interscience.wiley.com/ueic/ull_search_fs.html

25 Epichlorohydrin, trichloropropane and calcium chloride from the hypochlorination of allyl chloride

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Last changes: 2005

Acknowledgement

We thank Prof. Michael Overcash for the information provided in a personal communication.

25.1 Introduction

Epichlorohydrin (C_3H_5ClO, CAS-No. 106-89-8) – also called 1-chloro-2,3-epoxypropane, chloromethyl-oxirane or 1,2-epoxy-3-chloropropane – is the most important material for the production of epoxy resin.

Besides the epoxy resin, epichlorohydrin is used e.g. for the production of glycol or certain elastomers.

Calcium chloride (CaCl2, CAS-No 010043-52-4) has numerous uses, e.g. highway maintenance (melts ice), cold weather concrete additive, production of other calcium salts, etc.

1,2,3-trichloropropane (C3H5Cl3, CAS-No 96-18-4) is used as an intermediate in the synthesis of other chemicals. This chlorinated hydrocarbon gained notoriety, as its use as a solvent and degreasing agent resulted in water and groundwater pollution at numerous sites. It is listed as a substance reasonably anticipated to be a human carcinogen (cicads 56, 2003).

The information on epichlorohydrin in ecoinvent v 1.2 has been partially revised with regard to the coproducts, the chemical and physical properties, and chapter 12.6 ff

25.2 Reserves and Resources of Epichlorohydrin

Epichlorohydrin is a chlorinated organic chemical that is produced from the chlorohydrination of allyl chloride. Epichlorohydrin production capacities range from 21’000 to 250’000 metric tons per year, ABB Lummus, Shell and Solvay are leading producers. (Wells, 1999) 2000 production capacity in the EU was 290’000 metric tons (IPPC Chemicals, 2002).

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25.3 Characterisation of Epichlorohydrin

Epichlorohydrin is a colorless mobile liquid with an irritating odor. This substance is not very soluble in water but readily soluble in low molecular mass alcohols, esters, ethers, ketones or in aromatic hydrocarbons (Wells 1999).

Tab. 25.1 Chemical and physical properties of epichlorohydrin, calcium chloride and trichloropropane

Property	Epichlorohydrin	Calcium chloride	Trichloropropane	Unit	Remarks
Molecular weight	92.53 [1]	110.1 [2]	147.4 [3]	g mol-1	
Specific gravity	1.181 [1]	2.51 [2]	1.38 [3]	g cm-3	at 20° C
Boiling point	115.2 [1]	ng	156 [3]	° C	at normal pressure
Melting point	-58.1 [1]	30 [2]	- 14.7 [3]	° C	at normal pressure
Carbon content	0.389	0	0.244	kg kg-1	
Hydrogen content	0.054	0	0.034	kg kg-1	
Oxygen content	0.173	0	0	kg kg-1	
Chlorine content	0.3837	0.64	0.72	kg kg-1	

1 Source: Wells 1999

2 Source: Römpp, 9th edition, 1989

3 Source: Cicads 56, 2003

25.4 Use of Epichlorohydrin

Epichlorohydrin is primarily used for the manufacture of epoxy resins with Bisphenol A. The second major application is for the production of synthetic glycerine, although this use is waning with the increasing use of natural glycerine. Other outlets are in the manufacture of elastomers and textile additives (Wells, 1999).

25.5 System Characterisation (Overcash 1998 – 2004)

Epichlorohydrin is formed from allyl chloride, which is mixed with dilute hypochlorous acid to produce glycerol dichlorohydrin (80% conversion). The output is fed to a series of separators to isolate the glycerol dichlorohydrin, to recover the allyl chloride for recycle back to the reactor, and to remove the unreacted acid-water solution. (This solution is neutralized and sewered). The glycerol dichlorohydrin is mixed with a calcium hydroxide slurry and sent to the hydrolysis reactor. The reactor produces epichlorohydrin (90% conversion). The reactor bottom is a waste slurry of calcium chloride. The calcium chloride is sold as a by-product. The tops are gaseous epichlorohydrin, unreacted glycerol dichlorohydrin, organic by-products and some water vapor. These are removed from the top of the reactor and separated in a series of distillation columns. The glycerol dichlorohydrin is recycled and the organic by-products exit the system in a waste stream. Trichloropropane is sold as a by-product. The epichlorohydrin is recovered by adding acetic acid. The mixture is separated in a distillation column. The acetic acid-water mixture is neutralized and sewered. The epichlorohydrin distilled to remove a small amount of organic contaminants, producing 97 % pure epichlorohydrin.

Net Reaction (Aqueous Solution)

$$CH_2ClCH{=}CH_2 \quad + \quad HOCl \quad + \quad 1/2\ Ca(OH)_2 \quad \rightarrow \quad C_3H_5ClO \quad + \quad 1/2\ CaCl_2 \quad + \quad H_2O$$

Allyl Chloride	Hypochlorous Acid	Calcium Hydroxide	Epichlorohydrin	Calcium Chloride	Water

25.6 Life Cycle Inventories (Overcash 1998 – 2004)

25.6.1 Raw materials and auxiliaries

Epichlorohydrin is produced from allyl chloride, chlorine and calcium oxide. The input values are shown in Tab. 24.9

Tab. 25.2 Consumption of raw materials per metric ton epichlorohydrin

Input	Overcash 1998-2004
Allyl chloride (kg)	880.5
Chlorine (kg)	868
Calcium Oxide (kg)	693.2
Process Water (kg)	240.8

25.6.2 Energy

Overcash 1998 – 2004 reports a net energy input of 1.73 MJ/kg (includes recovered energy) and an electricity input of 0.075 kWh per kg epichlorohydrin.

Tab. 25.3 Energy consumption per kg epichlorohydrin

Input	**Overcash 1998 - 2004**
Steam (MJ)	1.73
Electricity (kWh)	0.075

25.6.3 Emissions to air

It is assumed that 100 % of the electricity consumed, i.e. 270 kJ/kg epichlorohydrin is converted to waste heat and that 100 % of the waste heat is released to the air. The following table gives pre-treatment values for the process emissions.

Tab. 25.4 Process emissions to air per kg epichlorohydrin

Output	
Waste heat (kJ)[1]	270
Allyl Chloride (g) [2]	17.61
Acetic Acid (g) [2]	0.07
Chlorine (g) [2]	4.34

1 Source: calculated from electricity input

2 Source: Overcash 1998 - 2004, pre-treatment values! Air emissions are assumed to be completely removed by scrubbers. It is further assumed that the inventory “disposal, solvents mixture, 16.5% water, to hazardous waste incineration” is an acceptable approximation.

25.6.4 Emissions to water

IPPC Chemicals, 2002 reports post-treatment values for the water emissions from epichlorohydrin manufacture given in the following table.

Tab. 25.5 Process emissions to water per kg epichlorohydrin

Output	
AOX (g)[1]	0.15
COD (g) [1]	3.5
BOD (g) [2]	3.5
DOC (g)[2]	1.3
TOC (g) [2]	1.3

1 Source: IPPC Chemicals, 2002

2 calculated

25.6.5 Infrastructure and land use

No information was readily available about infrastructure and land-use of epichlorohydrin plants. Therefore, in this study, the infrastructure is estimated based on the module "chemical plant, organics". This module assumes a built area of about 4.2 ha, an average output of 50'000 t/a, and plant life of fifty years. For this study, the estimated value is 4.00 E-10 units per kg of produced chemical.

25.7 Allocation of co-products

Within the production of epichlorohydrin two by-products that are sold on the market as also produced.. The yields of these co-products are given in Table 1.5.

As an allocation factor the weight of the product multiplied by its bulk shipping price (where available) was used. The used allocation factors are also given in Table 1.5.

Tab. 25.6 Allocation of epichlorohydrin and co-products

Process	**Hypochlorination of allyl chloride**			
	Unit	**Mass**	**Bulk price ($/lb)**	**Allocation factor**
Epichlorohydrin, from hypochlorination of allyl chloride, at plant, RER	kg	1000	0.98	82.4%
Calcium chloride, from hypochlorination of allyl chloride, at plant, RER	kg	1375	0.14	16.2%
Trichloropropane	kg	18	0.90 (assumed, based on epichlorohydrin and allyl chloride)	1.4%

25.8 Overview of input/output data and data quality considerations

The following table summarizes the input and out put data as well as the uncertainties used for the production of epichlorohydrin.

Tab. 25.7 Overview of input/output data and quality considerations for the manufacture of epichlorohydrin, calcium chloride and trichloropropane from the hypochlorination of allyl chloride

Input Category	Output Category	Name	Location	Category	Sub Category	Infra-structure Process	Unit	hypochlorination of allylic chlorid	Uncertainty Type	Standard Deviation 95%	General Comment	calcium chloride, from hypochlorination of allylic chlorid, at plant	epichlorhydrin, at plant	trichloropropane, from the hypochlorination of allylic chloride, at plant
		Location						RER				RER	RER	RER
		Infrastructure Process						0				No	No	No
		Unit						kg				kg	kg	kg
5	-	allylic chloride, at plant	RER	-	-	No	kg	8.80E-01	1	1.08	(2,2,1,3,1,1); literature	16.2	82.4	1.4
5	-	chemical plant, organics	RER	-	-	Yes	unit	4E-10	1	1.30	(4,5,na,na,na,na); infrastructure of a typical plant	16.2	82.4	1.4
5	-	chlorine, liquid, production mix, at plant	RER	-	-	No	kg	0.868	1	1.08	(2,2,1,3,1,1); literature	16.2	82.4	1.4
5	-	disposal, solvents mixture, 16.5% water, to hazardous waste incineration	CH	-	-	No	kg	0.022	1	1.21	(4,2,1,3,1,1); approximation	16.2	82.4	1.4
5	-	electricity, medium voltage, production UCTE, at grid	UCTE	-	-	No	kWh	0.08	1	1.08	(2,2,1,3,1,1); literature	16.2	82.4	1.4
5	-	heat, unspecific, in chemical plant	RER	-	-	No	MJ	1.73	1	1.08	(2,2,1,3,1,1); industry source	16.2	82.4	1.4
5	-	quicklime, milled, packed, at plant	CH	-	-	No	kg	0.693	1	1.08	(2,2,1,3,1,1); literature	16.2	82.4	1.4
5	-	transport, freight, rail	RER	-	-	No	tkm	1.5	1	1.30	(4,5,na,na,na,na); standard rail transport distance	16.2	82.4	1.4
5	-	transport, lorry 32t	RER	-	-	No	tkm	0.244	1	1.30	(4,5,na,na,na,na); standard trucking distance	16.2	82.4	1.4
5	-	treatment, sewage, unpolluted, to wastewater treatment, class 3	CH	-	-	No	m3	0.263	1	1.21	(4,2,1,3,1,1); approximation	16.2	82.4	1.4
5	-	water, completely softened, at plant	RER	-	-	No	kg	240	1	1.08	(2,2,1,3,1,1); literature	16.2	82.4	1.4
-	4	AOX, Adsorbable Organic Halogen as Cl	-	water	river	-	kg	0.00015	1	1.21	(4,2,1,3,1,1); calculation	16.2	82.4	1.4
-	4	BOD5, Biological Oxygen Demand	-	water	river	-	kg	3.500E-03	1	1.21	(4,2,1,3,1,1); calculation	16.2	82.4	1.4
-	4	COD, Chemical Oxygen Demand	-	water	river	-	kg	0.0035	1	1.21	(4,2,1,3,1,1); calculation	16.2	82.4	1.4
-	4	DOC, Dissolved Organic Carbon	-	water	river	-	kg	0.0013125	1	1.21	(4,2,1,3,1,1); calculation	16.2	82.4	1.4
-	4	TOC, Total Organic Carbon	-	water	river	-	kg	0.0013125	1	1.21	(4,2,1,3,1,1); calculation	16.2	82.4	1.4
-	4	Heat, waste	-	air	high population density	-	MJ	0.267	1	1.21	(4,2,1,3,1,1); estimated	16.2	82.4	1.4
-	2	calcium chloride, from hypochlorination of allylic chlorid, at plant	RER	-	-	No	kg	1.375				100	0	0
-	2	epichlorohydrin, at plant	RER	-	-	No	kg	1				0	100	0
-	2	trichloropropane, from the hypochlorination of allylic chloride, at plant	RER	-	-	No	kg	0.018				0	0	100

25.9 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 25.8 shows selected LCI results and the cumulative energy demand for the production of epichlorohydrin and its coproducts calcium chloride and trichloropropane.

Tab. 25.8 Selected LCI results and the cumulative energy demand for the production of epichlorohydrin and its coproduct calcium chloride

		Name		epichlorhydrin, at plant	calcium chloride, from hypochlorination of allylic chlorid, at plant	trichloropropane, from hypochlorination of allyl chloride, at plant
		Location		RER	RER	RER
		Unit	Unit	kg	kg	kg
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	56.1	8.0	53.0
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	15.0	2.1	14.1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.6	0.4	2.4
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.4	0.1	0.3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.8	0.1	0.8
LCI results						
resource	Land occupation	total	m2a	1.8E-1	2.5E-2	1.7E-1
air	Carbon dioxide, fossil	total	kg	3.0E+0	4.3E-1	2.8E+0
air	NMVOC	total	kg	1.6E-3	2.3E-4	1.5E-3
air	Nitrogen oxides	total	kg	7.0E-3	1.0E-3	6.6E-3
air	Sulphur dioxide	total	kg	9.1E-3	1.3E-3	8.6E-3
air	Particulates, < 2.5 um	total	kg	6.2E-4	8.9E-5	5.9E-4
water	BOD	total	kg	7.9E-3	1.1E-3	7.4E-3
soil	Cadmium	total	kg	3.3E-9	4.7E-10	3.1E-9

The cumulative energy demand for epichlorohydrin and trichloropropane are typical for chlorinated hydrocarbons. The emissions stem mostly from the combustion of the fossil fuels in upstream processes. The coproduct calcium chloride's emissions stem mostly from upstream energy processes as well. An exception in both cases is BOD, which also stems from downstream emissions.

Appendix: EcoSpold Meta Information

ReferenceFunction	Name	hypochlorination of allylic chlorid
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	5
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	13
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	Multi-output process that produces 1 kg epichlorohydrin, l.375 kg calcium chloride, and 0.018 kg trichloropropane, at plant. Economic allocation with allocation factor of 82.4% to epichlorohydrin.
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Hypochlorierung von Allylchlorid
ReferenceFunction	Synonyms	
ReferenceFunction	GeneralComment	Allyl chloride is reacted with hylochlorous acid and calcium chloride to produce epichlorohydrin, calcium chloride, trichloropropane and water
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	chemicals
ReferenceFunction	SubCategory	organics
ReferenceFunction	LocalCategory	Chemikalien
ReferenceFunction	LocalSubCategory	Organisch
ReferenceFunction	Formula	
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	
TimePeriod	StartDate	1998
TimePeriod	EndDate	2004
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	
Geography	Text	RER
Technology	Text	based on industry data in the US

References

Wells, 1999 G. Margaret Wells, “Handbook of Petrochemicals and Processes”, 2nd edition, Ashgate, 1999

IPPC Chemicals, 2002	European Commission, Directorate General, Joint Research Center, “Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry”, February 2002
Overcash, 1998 - 2004	Overcash, M., Chemical life cycle database, Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27695-7905
Römpp, 9th edition, 1989	Römpp Chemie Lexikon, Georg Thieme Verlag Stuttgart, Vol 1, 1989
Cicads 56, 2003	1,2,3-Trichloropropane, Concise International Chemical Assessment Document 56, WHO 2003

26 Potassium hydroxide, 90% pure

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Review: Niels Jungbluth, ESU-services, Uster
Last changes: 2005

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26.1 Introduction

This chapter describes the production of potassium hydroxide, also known as caustic potash, potassa, potash lye and potassium hydrate CAS-no 1310-58-3. This chemical is used primarily for potassium phosphates, as well as potassium soaps and detergents.

26.2 Reserves and Resources of Potassium Hydroxide

Caustic potash is an inorganic chemical with the formula KOH. It is manufactured from electrolysis of potassium chloride brine. It is a traditional ingredient in the making of soap, and for this purpose was historically obtained by steeping wood ash in water for a long period. The greatest demand for potash has been in its use for fertilizers. (www.answers.com)

26.3 Characterisation of Potassium Hydroxide

Potassium hydroxide is a solid (flakes) at room temperature. It is highly flammable and corrosive.

Tab. 26.1 Chemical and physical properties of caustic potash (according to www.chemexper.com)

Property	Unit	Value
Formula weight	56.10	g mol^{-1}
Boiling point	1320	°C at normal pressure
Melting point	360 *	°C at normal pressure
Density at 20 °C	2.04	g/ml
Potassium content	0.70	kg kg^{-1}
Oxygen content	0.29	kg kg^{-1}
Hydrogen content	0.02 **	kg kg^{-1}

*** 406 °C according to (UNEP 2002)**

**** total may not add up to 100% due to rounding**

26.4 Use / Application of Potassium Hydroxide

The following table provides an overview of potassium hydroxide uses

Caustic potash has many industrial uses; less than 2% is for wide dispersive use. It is used in chemical manufacturing, chemicals, fertilizers and other uses. (UNEP, 2002).

The following table summarizes the main uses on a global level (UNEP 2002):

Tab. 26.2 Main uses of potassium hydroxide

Use	Percentage
Potassium carbonate	26
chemical manufacturing	16
potassium chemicals	12
fertilizers	11
phosphates	9
agricultural chemicals	7
alkaline batteries	6
Remainder / all others	8

US projected demand for 2005 is estimated at about 470 thousand metric tons (Chemical Profiles). Estimated world-wide demand of potassium hydroxide was higher than 1 million metric tons expressed as KOH 100% in 1994. The global demand is expected to grow with 4.0% per year. (UNEP, 2002)

26.5 System Characterisation (Overcash, 1998 - 2004)

Potassium hydroxide is manufactured by the electrolysis of potassium chloride brine in electrolytical cells. Hydrogen and chlorine are withdrawn from the cell. The rest of the reaction mixture contains KOH, water, and unreacted potassium chloride. This reaction mixture is then concentrated in an evaporator. Most of the potassium chloride crystallizes by evaporation, and is recycled. After evaporation, the potassium hydroxide is precipitated.

$2\ KCl + 2\ H2O \rightarrow 2\ KOH + Cl2 + H2 \qquad (1)$

(1) production of potassium hydroxide, chlorine and hydrogen from potassium chloride brine

26.6 Life Cycle Inventory of Potassium Hydroxide, 90% pure

26.6.1 Precursor materials

Tab. 26.3 Raw materials for caustic potash production

Precursor	Consumption in kg per metric ton of caustic potash produced
Potassium chloride	823 *
Water	2195

*** The inventory “potassium chloride as K2O, at regional storehouse” refers to 1.67 kg KCl. Therefore, a total of 492.8 kg potassium chloride as K2O is entered.**

Next to 1 kg product caustic potash the outcome consists of

- 0.023 kg insolubles (removed from brine) (1)
- 0.257 kg filter waste (2) and 1.814 kg evaporated water.

(1) the insolubles are naturally occurring salts of Ca, Mg, and some metals. This is a solid waste and its disposal is approximated with the inventory “disposal, salt tailings potash mining, 0% water, to residual material landfill”.

(2) the filter waste is about 3% KCl, 5% KOH, and the balance (0.237 kg) is water. It is assumed that this effluent is discharged to a class 3 wastewater treatment plant. The remaining 144 kg of water is assumed to be part of

the final product. The product is sold as 90% pure.

26.6.2 Energy usage

Electrical power usage comprises 6.52 MJ / kg of product.

Net steam usage is 6.2 MJ / kg product. The potential heat recovery from exchangers is included in this figure.

26.6.3 Emissions

Tab. 26.4 Emissions from KOH production

Chemical	Pre-treatment values (kg)			Comments
	Air	Liquid	Solid	
KCl (Potassium chloride)		0.008		dissolved in water before release to the environment.
KOH		0.012		Is assumed to be neutralized by residual acid from another process or is recycled
Insolubles			0.023	the insolubles are naturally occurring salts of Ca, Mg, and some metals. They are assumed to be landfilled according to “disposal, salt tailings potash mining, 0% water, to residual material landfill”.

* The emissions of potassium chloride are treated as chloride emissions

26.6.4 Infrastructure and transports

No information was readily available. For this reason, the dataset “chemical plant, organics” is used as an approximation. This assumes a production capacity of 50’000 tons/year and a plant life of fifty years, which translates to 0.0000000004 units per kg of produced KOH.

Transport distances are taken from (Frischknecht et al., 2003).

26.7 Overview of input/output data and data quality considerations

The following table summarizes the input and out put data as well as the uncertainties used for the production of caustic potash.

Tab. 26.5 Overview of input/output data and quality considerations for the manufacture of caustic potash

Input Category	Output Category	Name	Location	Category	Sub Category	Infra-structure Process	Unit	potassium hydroxide, at regional storage	Uncertainty Type	Standard Deviation 95%	General Comment
		Location						RER			
		Infrastructure Process						0			
		Unit						kg			
5	-	chemical plant, organics	RER	-	-	Yes	unit	4E-10	1	1.30	(4,5,na,na,na,na); infrastructure of a typical plant
5	-	disposal, salt tailings potash mining, 0% water, to residual material landfill	CH	-	-	No	kg	0.023	1	1.21	(4,2,1,3,1,1); approximation
5	-	electricity, medium voltage, production UCTE, at grid	UCTE	-	-	No	kWh	1.81	1	1.08	(2,2,1,3,1,1); literature
5	-	heat, unspecific, in chemical plant	RER	-	-	No	MJ	6.2	1	1.08	(2,2,1,3,1,1); industry source
5	-	potassium chloride, as K2O, at regional storehouse	RER	-	-	No	kg	4.93E-01	1	1.08	(2,2,1,3,1,1); literature
5	-	transport, freight, rail	RER	-	-	No	tkm	0.4938	1	1.30	(4,5,na,na,na,na); standard rail transport distance
5	-	transport, lorry 32t	RER	-	-	No	tkm	0.0823	1	1.30	(4,5,na,na,na,na); standard trucking distance
5	-	treatment, sewage, to wastewater treatment, class 3	CH	-	-	No	m3	0.000257	1	1.21	(4,2,1,3,1,1); approximation
5	-	water, completely softened, at plant	RER	-	-	No	kg	2.195	1	1.11	(2,2,1,3,1,1); literature
4	-	Water, cooling, unspecified natural origin	-	resource	in water	-	m3	0.0022	1	1.08	(2,2,1,3,1,1); literature
-	4	Chloride	-	water	river	-	kg	0.038	1	1.21	(4,2,1,3,1,1); calculation
-	4	Heat, waste	-	air	high population density	-	MJ	6.52	1	1.21	(4,2,1,3,1,1); estimated
-	4	Potassium, ion	-	water	river	-	kg	0.013	1	1.21	(4,2,1,3,1,1); calculation
-	0	potassium hydroxide, at regional storage	RER	-	-	No	kg	1			

26.8 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 26.6 shows selected LCI results and the cumulative energy demand for the production of potassium hydroxide.

Tab. 26.6 Selected LCI results and the cumulative energy demand for the production of potassium hydroxide

		Name		potassium hydroxide, at regional storage
		Location		RER
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	24.8
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	9.8
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.6
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.2
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.4
LCI results				
resource	Land occupation	total	m2a	9.8E-2
air	Carbon dioxide, fossil	total	kg	1.7E+0
air	NMVOC	total	kg	6.7E-4
air	Nitrogen oxides	total	kg	3.2E-3
air	Sulphur dioxide	total	kg	5.0E-3
air	Particulates, < 2.5 um	total	kg	3.5E-4
water	BOD	total	kg	1.8E-3
soil	Cadmium	total	kg	1.5E-9

The cumulative energy demand for potassium hydroxide reflects that relatively high portion of electrical energy, which is almost as high as the required thermal energy (steam). The emissions and land use reflect the energy input.

Appendix: EcoSpold Meta Information

ReferenceFunction	Name	potassium hydroxide, at regional storage
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	1
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	13
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	cradle-to-gate, including all precursors, ancillary materials and transports
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Kaliumhydroxid, ab Regionallager
ReferenceFunction	Synonyms	
ReferenceFunction	GeneralComment	Potassium hydroxide is manufactured by the electrolysis of potassium chloride brine in electrolytical cells
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	chemicals
ReferenceFunction	SubCategory	inorganics
ReferenceFunction	LocalCategory	Chemikalien
ReferenceFunction	LocalSubCategory	Anorganisch
ReferenceFunction	Formula	KOH
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	001310-58-3
TimePeriod	StartDate	1998
TimePeriod	EndDate	2004
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	
Geography	Text	RER
Technology	Text	based on industry data in the US

References

UNEP, 2002 UNEP Publications, OECD SIDS, “Potassium Hydroxide”, January 2002

Chemical Market Reporter	a publication of the Schnell Publishing Company, a member of the Reed Elsevier group
Overcash, 1998 - 2004	Overcash, M., Chemical life cycle database, Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27695-7905

27 Synthetic glycerine

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Review: Niels Jungbluth, ESU-services, Uster
Last changes: 2005

Acknowledgement

We thank Prof. Michael Overcash for the information provided in a personal communication.

27.1 Introduction

This chapter describes the production of synthetic glycerine, also known as glycerol, 1,2,3-trihydroxypropane, 1,2,3-propanetriol, glycol alcohol, CAS-no 56-81-5. This chemical is used primarily for food products, as well as soap products.

27.2 Reserves and Resources of Synthetic Glycerine

Glycerine is an organic chemical with the formula $C_3H_8O_3$. It occurs in natural fats and oils. About 90% of glycerine is obtained from natural sources and under 10% from synthetic production (Wells, 1999).

27.3 Characterisation of Synthetic Glycerine

Glycerine is a colorless, oily liquid with a sweet taste.

Tab. 27.1 Chemical and physical properties of synthetic glycerine

Property	Value	Unit	Remarks
Molecular weight [1]	92.09	g mol^{-1}	
Specific gravity [1]	1.26	g/ml	at 20° C
Boiling point [1]	290	° C	decomposes
Melting point [1]	18	° C	at normal pressure
Heat of combustion, net caloric value (LHV)[2]	4271.	cal/g	
Carbon content	0.391	kg kg^{-1}	
Hydrogen content	0.087	kg kg^{-1}	
Oxygen content	0.521	kg kg^{-1}	

1 Source: Wells, 1999

2 Source: Mellin, J., 2002

27.4 Use of Synthetic Glycerine

Glycerine is used in a large number of applications in the pharmaceutical, toiletries and cosmetics industries. Because of its low toxicity, it is used in such products as toothpaste, facial creams or emulsifiers in ice cream (glycerine esters). Other outlets are in the manufacture of alkyd resins and polyesters.

Synthetic glycerine production is steadily decreasing. Capacities range from 8000 to 63’000 metric tons per year, Dow Chemical is the leading producer. In 1998 estimated world production was 95’000 metric tons (HB International). 2001 production in the US was 68’180 metric tons (Chemical Market Reporter).

27.5 System Characterisation

There are three routes for the manufacture of synthetic glycerine, all of which use propylene as a precursor. These routes involve the one of the following intermediates:

- epichlorohydrin
- acrolein
- allyl alcohol

The epichlorohydrin route is the only one which is important industrially (Wells, 1999).

In this process, glycerine is produced by reacting epichlorohydrin with a 10% sodium hydroxide aqueous solution. This reaction produces sodium chloride, which is removed. The process stream is cooled and unreacted epichlorohydrin removed. The process stream is purified, which removes 88% NaOH. The distillate consists of 82% glycerine, 17% steam, and 1% impurities. The liquid glycerine is separated from the steam and the exiting product stream, containing 99% glycerine, is cooled using a heat exchanger.

$$C3H5ClO + NaOH + H2O \rightarrow C3H5(OH)3 + NaCl \qquad (1)$$

(1) production of glycerine and sodium chloride from epichlorohydrin, caustic soda and water

27.6 Life cycle inventory of glycerine (Overcash, 1998 - 2004)

27.6.1 Precursor materials

Synthetic glycerine is produced from epichlorohydrin, sodium hydroxide and water. The input values are shown in the following table.

Tab. 27.2 Raw materials for glycerine production

Input	Consumption in kg per tonne of glycerine produced
Epichlorohydrin	1015
Sodium hydroxide	440
Water	3900

The product glycerine is 99% pure. Product per metric ton also contains the following impurities, which amount to the remaining 1%:

- 1.25 kg Epichlorohydrin,
- 1.25 kg NaOH, and
- 7.5 kg NaCl

Furthermore, 3’749 kg water are contained in the process emissions.

27.6.2 Energy usage

Electrical power usage stems from the operation of pumps, the cyclone, mixer, etc. and comprises 23.3 MJ / metric ton of product.

Net steam usage is 9’275 MJ / metric ton of product. The potential heat recovery from exchangers is included in this figure.

27.6.3 Emissions

The following table contains pre-treatment values for emissions from the production of synthetic glycerine.

Tab. 27.3 emissions from glycerine production

Chemical	Pre-treatment values (g/kg)			Comments
	Air	Liquid	Solid	
Chloroform ($CHCl_3$)	0.2*	2.4		Air emissions are assumed to be completely removed by scrubbers; the wastewater halogenated emissions can be reduced by 90% (IPPC Chemicals, 2002, Chapter 3.6)
Epichlorohydrin		17.8		See above
NaOH		8.8		Is assumed to be neutralized by residual acid from another process or is recycled
NaCl		630		dissolved in water before release to the environment.

* The emissions of sodium chloride from chemical treatment are assumed to be part of total NaCl emissions. Furthermore, a total of 3.75 kg water is emitted per kg product. This water is assumed to be sewered.

27.6.4 Infrastructure and transports

No information was readily available. For this reason, the inventory “chemical plant, organics” was used as an approximation. This inventory assumes a production capacity of 50’000 tons/year and a plant life of fifty years, which translates to 0.0000000004 units per kg of produced synthetic glycerine.

Transport distances are taken from (Frischknecht et al., 2003).

Overview of input/output data and data quality considerations

Tab. 27.4 Unit process raw data of synthetic glycerine

Input Category	Output Category	Name	Location	Category	Sub Category	Infra-structure Process	Unit	glycerine, from epichlorohydrin, at plant	Uncertainty Type	Standard Deviation 95%	General Comment			
		Location						RER						
		Infrastructure Process						0						
		Unit						kg						
5	-	chemical plant, organics	RER	-	-	Yes	unit	4E-10	1	1.30	(4,5,na,na,na,na); infrastructure of a typical plant			
5	-	electricity, medium voltage, production UCTE, at grid	UCTE	-	-	No	kWh	0.01	1	1.08	(2,2,1,3,1,1); literature			
5	-	epichlorhydrin, at plant	RER	-	-	No	kg	1.02E+00	1	1.08	(2,2,1,3,1,1); literature			
5	-	heat, unspecific, in chemical plant	RER	-	-	No	MJ	9.27	1	1.08	(2,2,1,3,1,1); industry source			
5	-	sodium hydroxide, 50% in H2O, production mix, at plant	RER	-	-	No	kg	0.44	1	1.11	(2,2,1,3,1,1); literature			
5	-	transport, freight, rail	RER	-	-	No	tkm	0.873	1	1.30	(4,5,na,na,na,na); standard rail transport distance			
5	-	transport, lorry 32t	RER	-	-	No	tkm	0.0823	1	1.30	(4,5,na,na,na,na); standard trucking distance			
5	-	treatment, sewage, to wastewater treatment, class 3	CH	-	-	No	m3	0.00375	1	1.21	(4,2,1,3,1,1); approximation			
5	-	water, completely softened, at plant	RER	-	-	No	kg	3.9	1	1.11	(2,2,1,3,1,1); literature			
-	4	AOX, Adsorbable Organic Halogen as Cl	-	water	river	-	kg	0.00078	1	1.08	(2,2,1,3,1,1); calculated			
-	4	BOD5, Biological Oxygen Demand	-	water	river	-	kg	0.00192	1	1.11	(2,2,1,3,1,1); literature			
-	4	Chloride	-	water	river	-	kg	0.382	1	1.21	(4,2,1,3,1,1); calculation			
-	4	COD, Chemical Oxygen Demand	-	water	river	-	kg	0.00192	1	1.11	(2,2,1,3,1,1); literature			
-	4	DOC, Dissolved Organic Carbon	-	water	river	-	kg	0.0006	1	1.21	(4,2,1,3,1,1); calculation			
-	4	Heat, waste	-	air	high population density	-	MJ	0.0233	1	1.21	(4,2,1,3,1,1); estimated			
-	4	Sodium, ion	-	water	river	-	kg	0.023	1	1.21	(4,2,1,3,1,1); approximation			
-	4	TOC, Total Organic Carbon	-	water	river	-	kg	0.0006	1	1.11	(2,2,1,3,1,1); literature			
-	0	glycerine, from epichlorohydrin, at plant	RER	-	-	No	kg	1						

27.7 Cumulative Results and Interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

Tab. 27.5 shows selected LCI results and the cumulative energy demand for the production of synthetic glycerine.

Tab. 27.5 Selected LCI results and the cumulative energy demand for the production of synthetic glycerine

		Name		glycerine, from epichlorohydrin, at plant
		Location		RER
		Unit	Unit	kg
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	77.3
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	20.3
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.6
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.5
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.1
LCI results				
resource	Land occupation	total	m2a	2.5E-1
air	Carbon dioxide, fossil	total	kg	4.4E+0
air	NMVOC	total	kg	2.2E-3
air	Nitrogen oxides	total	kg	9.3E-3
air	Sulphur dioxide	total	kg	1.3E-2
air	Particulates, < 2.5 um	total	kg	8.6E-4
water	BOD	total	kg	1.2E-2
soil	Cadmium	total	kg	4.8E-9

The cumulative energy demand for synthetic glycerine stems mostly from epichlorohydrin. The emissions and land use stem mostly from the epichlorohydrin as well as from the energy usage.

Appendix: EcoSpold Meta Information

ReferenceFunction	Name	glycerine, from epichlorohydrin, at plant
Geography	Location	RER
ReferenceFunction	InfrastructureProcess	0
ReferenceFunction	Unit	kg
DataSetInformation	Type	1
DataSetInformation	Version	1.0
DataSetInformation	energyValues	0
DataSetInformation	LanguageCode	en
DataSetInformation	LocalLanguageCode	de
DataEntryBy	Person	13
DataEntryBy	QualityNetwork	1
ReferenceFunction	DataSetRelatesToProduct	1
ReferenceFunction	IncludedProcesses	cradle-to-gate, including all precursors, ancillary materials and transports
ReferenceFunction	Amount	1
ReferenceFunction	LocalName	Glycerin, aus Epichlorhydrin, ab Werk
ReferenceFunction	Synonyms	
ReferenceFunction	GeneralComment	The reaction of epichlorohydrin with caustic delivers synthetic glycerine. This production route is of decreasing importance, as glycerine from natural sources is gaining market shares.
ReferenceFunction	InfrastructureIncluded	
ReferenceFunction	Category	chemicals
ReferenceFunction	SubCategory	organics
ReferenceFunction	LocalCategory	Chemikalien
ReferenceFunction	LocalSubCategory	Organisch
ReferenceFunction	Formula	C3H8O3
ReferenceFunction	StatisticalClassification	
ReferenceFunction	CASNumber	000056-81-5
TimePeriod	StartDate	1998
TimePeriod	EndDate	2004
TimePeriod	DataValidForEntirePeriod	1
TimePeriod	OtherPeriodText	
Geography	Text	RER
Technology	Text	based on industry data in the US

References

Mellin, J	Heat of Combustion of Glycerine and Organic Oils: A comparison of two olive oils http://www.seas.upenn.edu/courses/belab/LabProjects/2002/be210s02w4.doc
Wells, 1999	G. Margaret Wells, “Handbook of Petrochemicals and Processes”, 2nd edition, Ashgate, 1999
IPPC Chemicals, 2002	European Commission, Directorate General, Joint Research Center, “Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry”, February 2002
Chemical Market Reporter	a publication of the Schnell Publishing Company, a member of the Reed Elsevier group
Overcash, 1998 - 2004	Overcash, M., Chemical life cycle database, Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27695-7905
HB International	http://www.dainet.de/fnr/ctvo/byproducts/heming_hbi.doc

28 Naphtha, to molecular sieve

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Last changes: 2006

Acknowledgement

We thank Michael Overcash for the information provided in a personal communication.

28.1 Introduction

The separation of naphtha with a molecular sieve is a multi-output process. The following processes were modelled:

- n-hexane, at plant, RER
- n-heptane, at plant, RER
- fraction 1 from naphtha, at plant, RER
- 2,3-dimethylbutane, at plant, RER
- 2-methylpentane, at plant, RER
- methylcyclopentane, at plant, RER
- 1,1-dimethylcyclopentane, at plant, RER
- methylcyclohexane, at plant, RER
- fraction 7 from naphtha, at plant, RER
- fraction 8 from naphtha, at plant, RER

The chemical and physical properties of the most important products are given here.

Hexane (C_6H_{14}, CAS-No. 110-54-3)

Tab. 28.1 Chemical and physical properties of n-hexane (Bhattacharjee 2005, Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	86.2	
Specific gravity (kg m-3)	659,37	at 20° C
Melting point (° C)	-95.3	at normal pressure
Boiling point (° C)	68.7	at normal pressure
Carbon content (kg kg-1)	0.81	
Hydrogen content (kg kg-1)	0.19	

Heptane (C_7H_{16}, CAS-No. 182-82-5)

Tab. 28.2 Chemical and physical properties of n-heptane (Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	100.2	
Specific gravity (kg m-3)	683.8	at 20° C
Melting point (° C)	-90.6	at normal pressure
Boiling point (° C)	98.4	at normal pressure
Carbon content (kg kg-1)	0.84	
Hydrogen content (kg kg-1)	0.16	

2,3-Dimethylbutane (C_6H_{14}, CAS-No. 79-29-8)

Tab. 28.3 Chemical and physical properties of 2,3-dimethylbutane (Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	86.2	
Specific gravity (kg m-3)	661.6	at 20° C
Melting point (° C)	-128.5	at normal pressure
Boiling point (° C)	58	at normal pressure
Carbon content (kg kg-1)	0.837	
Hydrogen content (kg kg-1)	0.163	

2-Methylpentane (C_6H_{14}, CAS-No. 107-83-5)

Tab. 28.4 Chemical and physical properties of 2-methylpentane (Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	86.2	
Specific gravity (kg m-3)	653.2	at 20° C
Melting point (° C)	-153.7	at normal pressure
Boiling point (° C)	60.3	at normal pressure
Carbon content (kg kg-1)	0.837	
Hydrogen content (kg kg-1)	0.163	

Methylcyclopentane (C_6H_{12}, CAS-No. 96-37-7)

Tab. 28.5 Chemical and physical properties of 2-methylpentane (Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	84.2	
Specific gravity (kg m-3)	748.6	at 20° C
Melting point (° C)	-142.5	at normal pressure
Boiling point (° C)	71.8	at normal pressure
Carbon content (kg kg-1)	0.857	
Hydrogen content (kg kg-1)	0.143	

Methylcyclohexane (C_7H_{14}, CAS-No. 108-87-2)

Tab. 28.6 Chemical and physical properties of methylcyclohexane (Ullmann 2005)

Property	Value	Remarks
Molecular weight (g mol-1)	98.1	
Specific gravity (kg m-3)	769.4	at 20° C
Melting point (° C)	-126.6	at normal pressure
Boiling point (° C)	100.9	at normal pressure
Carbon content (kg kg-1)	0.857	
Hydrogen content (kg kg-1)	0.143	

28.2 Characterisation of the production process

The separation of *n*-alkanes from *iso*-alkanes on 5A zeolites is of importance in the mineral oil industry. For example, Pressure Swing Adsorption (PSA) processes have been developed by UOP (Isosiv), Texaco (TSF), Leuna (Parex-Leuna), ELF (N-Iself), Exxon, and BP. In these processes, regeneration is sometimes performed by displacement media such as NH_3 or short chain *n*-alkanes. The Molex process of UOP is a liquid-phase process designed on the principle of simulated countercurrent chromatography (Sorbex technology, Fig. 28.1). All these processes are based on the fact that *n*-alkanes are adsorbed by 5A zeolites, while *iso*-alkanes are too bulky to enter the pore system and therefore break through immediately. The Molex process is a continuous process whereas in other separation techniques the sieves have to be reactivated by thermal sewing, vacuum desorption or gas displacement. The regeneration mode is based on the feed composition.

The properties of the zeolite 5A, which is sold by Zhengshou Gold Mountain Science and Technique Ltd., are given in Fig. 28.1.

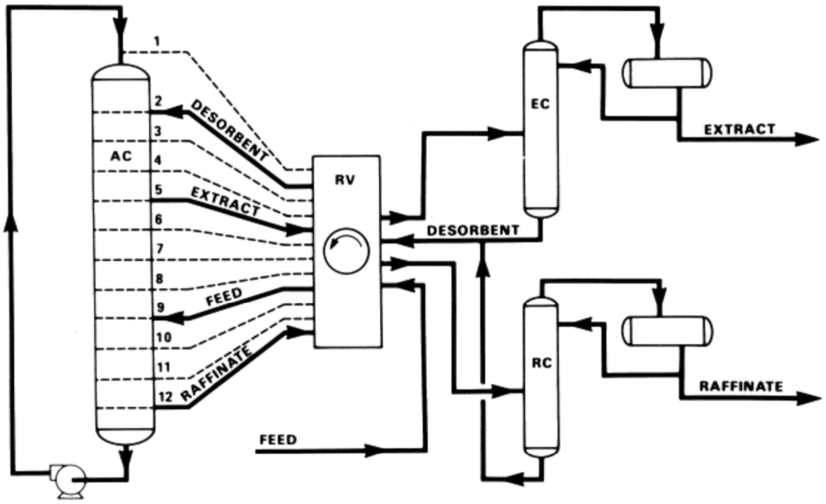

Fig. 28.1 The Sorbex process (taken from Ruthven 2004, Figure 14)

AC: adsorbent chamber, RV: rotary wave, EC: extraction column, RC: raffinate column

Tab. 28.7 Specification of different types of zeolith 5A (Zhengshou 2004)

Property	5A-1	5A-2	H5A
Bead size (mm)	2.0-2.8	2.8-4.75	2.0-2.5
Bulk density (kg/m3)	680	670	680
Crushing strength (N)	30	70	50
Attrition loss (% wt)	0.2	0.2	0.1
Moisture capacity (50 % RH/25 °C, mg/g) ≥	210	210	250
Loss on ignition (575 °C/3h,%wt)	1.5	1.5	1.5
n-Hexane capacity (mg/g)	125	125	145

28.3 Use

Pure *n*-Hexane is used for the extraction of vegetable oils (e.g., from soybeans), as a solvent in chemical reactions (e.g., for coordination complex catalyzed polymerization of olefins) and in adhesive formulations.

28.4 System Characterisation

This report corresponds to the dataset for the multi-output process **naphtha, to molecular sieve, at plant, in Europe**. The data, which are given in this report, are based on the separation of 1 kg naphta. The system includes the process with consumption of raw materials, energy, infrastructure and land use, as well as the generation of emissions to air and water. It also includes transportation of the raw materials. For the study transient or unstable operations like starting-up or shutting-down, are not included, but the production during stable operation conditions. Storage and transportation of the final product are neither included. It is assumed that the manufacturing plants are located in an urban/industrial area and consequently the emissions are categorised as emanating in a high population density area. The emissions into water are assumed to be emitted into rivers. It is assumed that 100% of the electricity consumed is converted to waste heat and that 100% of the waste heat is released to the air.

The molecular sieve separation of naphtha is a multioutput process with the following products (Overcash 1998-2004):

- ***n*-Hexane**
- ***n*-Heptane**
- **Fraction 1** (cyclopentane, 2,2-dimethylbutane)
- **Fraction 2** (2,3-dimethylbutane)
- **Fraction 3** (2-methylpentane)
- **Fraction 4** (methylcyclopentane)
- **Fraction 5** (1,1-dimethylcyclopentane)
- **Fraction 6** (methylcxyclohexane)
- **Fraction 7** (2,2,-dimethylpentane, 2,4-dimethylpentane, cyclohexane)
- **Fraction 8** (2-methylpentane, 2,3-dimethylpentane, trans-1,2-dimethylcyclo-pentane, 3-methylhexane)

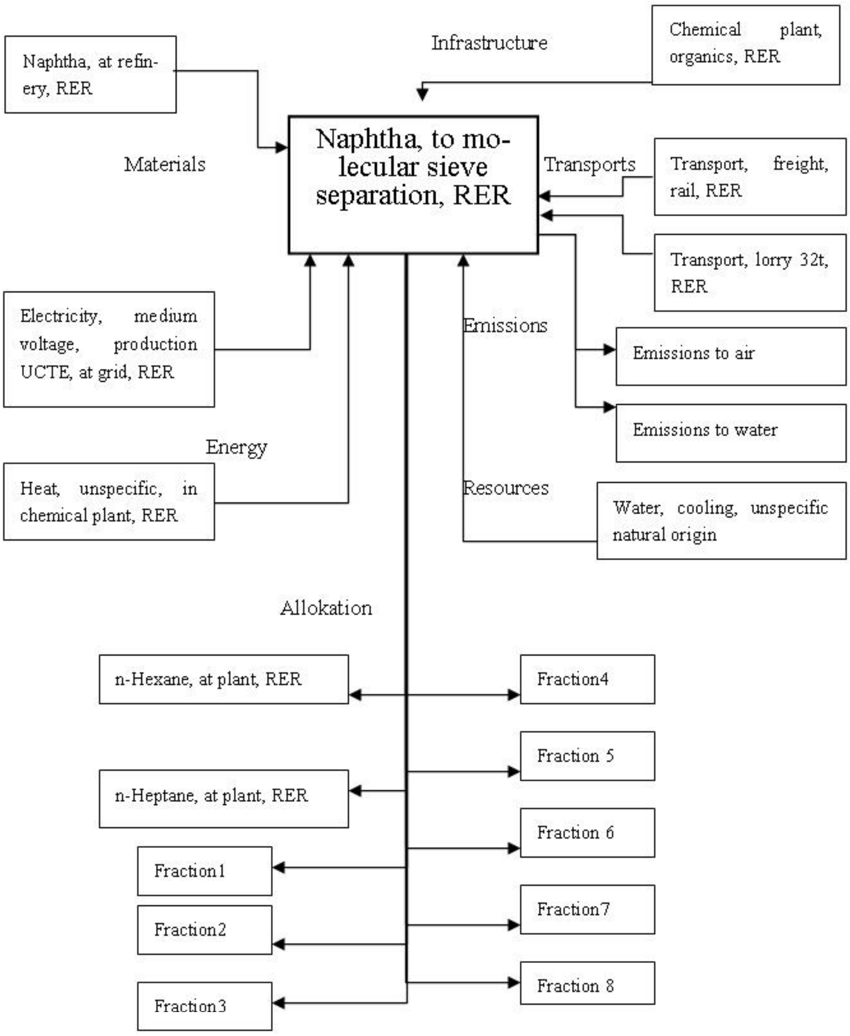

Fig. 28.2 **Process chain for the molecular sieve separation of naphtha**

28.5 Molecular sieve separation process

28.5.1 Data sources

The data, which are used in this inventory, derive from personal communication from Michael Overcash. They are based on data from the Chemical life cycle database, which has been created at the North Carolina State University (Overcash 1998 – 2004).

28.5.2 Raw materials and auxiliaries

With Overcash 1998 – 2004 a recovery of 97.2 % is achieved, with losses of about 1.4 % and final residue of 1.4 %.

Tab. 28.8 Consumption of raw materials for the molecular sieve separation of naphtha (Overcash 1998-2004)

Input	Per kg naphtha
Naphtha (kg)	1
Cooling water (kg)	25

28.5.3 Energy

Overcash 1998 – 2004 reports a heating energy input of 27064.14 kJ and an electricity input of 0.246 kJ per kg n-hexane. As a potential heat recovery of 5737.36 kJ/kg is considered, the value for the steam input in this inventory is the difference between the heating energy and the recovered energy.

Tab. 28.9 Energy consumption for the molecular sieve separation of naphtha (Overcash 1998-2004)

Input	Per kg naphtha
Steam (MJ)	3.11
Electricity (kWh)	9.96E-06

28.5.4 Transportation

No information is available in the sources consulted concerning transportation of the raw materials. Therefore, the following standard distances as defined in Frischknecht 2003 are used: 100 km by lorry 32t and 600 km by train for naphtha. Tab. 28.10 summarises the total transport amounts for the production of 1 kg *n*-hexane.

Tab. 28.10 Total transport amounts for the molecular sieve separation of naphtha (Overcash 1998-2004)

	tkm kg^{-1} naphtha
lorry	0.1
rail	0.6

28.5.5 Infrastructure and land use

No information was readily available about infrastructure and land-use of *n*-hexane plants. Therefore, in this study, the infrastructure is estimated based on the module "chemical plant, organics". This module assumes a built area of about 4.2 ha, an average output of 50'000 t/a, and plant life of fifty years. For this study, the estimated value is 4.00 E-10 units per kg of produced chemical.

28.5.6 Emissions to air

It is assumed that 100 % of the electricity consumed, i.e. 6.83E-05 kWh/kg hexane is converted to waste heat and that 100 % of the waste heat is released to the air. Overcash 1998 – 2004 reports values emissions to air from the molecular sieve separation of naphtha.

Tab. 28.11 Process emissions to air from the molecular sieve separation of naphtha

Output	Per kg naphtha
Waste heat (MJ)[1]	3.59E-05
Hexane (kg) [2]	1.68E-03
Heptane (kg) [2]	2.01E-03
Hydrocarbons (kg)[2]	1.03E-02
Carbon dioxide, fossil (kg) [3]	5.54E-02

1 Source: calculated from electricity input

2 Source: Overcash 1998 - 2004

3 calculated from the water treatment

28.5.7 Emissions to water

Overcash 1998 – 2004 reports values for the water emissions from the molecular sieve separation of naphtha. It was assumed that the wastewater is treated in an internal wastewater plant. The removal efficiency for the hydrocarbons was assumed with 90%. The carbon contained in the removed hydrocarbons was accounted as CO_2 emissions to air.

The values for COD, BOD, TOC, and DOC used in this inventory were calculated from the amount of the emissions in the treated wastewater assuming a carbon conversion of 96% for COD. For the calculation of the values for BOD and DOC the worst-case scenario BOD = COD and TOC = DOC was used. A summary of the values used in this inventory is given in Tab. 28.12.

Tab. 28.12 Process emissions to water from the molecular sieve separation of naphtha

Output	Per kg naphtha
Hydrocarbons, unspecified (kg)[1]	1.4E-03
BOD, COD (kg) [2]	1.89E-02
TOC, DOC (kg) [2]	4.74E-03

1 Source: Overcash 1998 - 2004

2 Source: calculated from the water emissions

28.6 Allocation of the co-products of the molecular sieve separation of naphtha

Within the production of n-hexane by molecular sieve separation of naphtha, n-heptane, fraction 1 (cyclopentane, 2,2-dimethylbutane), fraction 2 (2,3-dimethyl-butane), fraction 3 (2-methylpentane), fraction 4 (methylcyclopentane), fraction 5 (1,1-dimethylcyclopentane), fraction 6 (methylcxyclohexane), fraction 7 (2,2,-dimethylpentane, 2,4-dimethylpentane, cyclohexane), and fraction 8 (2-methyl-pentane, 2,3-dimethylpentane, trans-1,2-dimethylcyclopentane, 3-methylhexane) are obtained as co-products. The yields of the diverse co-products are given in Tab. 28.13.

As allocation factor the weight of the products was used. The used allocation factors are given in Tab. 28.13.

Tab. 28.13 Allocation of n-hexane and the co-products from molecular sieve separation of naphtha

Process	**Naphtha, to molecular sieve separation, RER**			
	Unit	**per kg hexane**	**per kg naphtha**	**Allocation factor**
n-hexane, at plant, RER	kg	1	0.14588	0.15009
n-heptane, at plant, RER	kg	0.97490	0.14222	0.14632
fraction 1 from naphtha, at plant, RER	kg	0.09754	0.01423	0.01464
2,3-dimethylbutane, at plant, RER	kg	0.06654	0.00971	0.00999
2-methylpentane, at plant, RER	kg	0.32752	0.04778	0.04916
methylcyclopentane, at plant, RER	kg	0.39946	0.05827	0.05995
1,1-dimethylcyclopentane, at plant, RER	kg	0.10973	0.01601	0.01647
methylcyclohexane, at plant, RER	kg	1.14875	0.16758	0.17241
fraction 7 from naphtha, at plant, RER	kg	0.57824	0.08436	0.08678
fraction 8 from naphtha, at plant, RER	kg	1.96017	0.28596	0.29419
Total	kg	6.85479	0.97200	1.00000

28.7 Data Quality Considerations

Tab. 28.14 shows the data quality indicators of the inventory of the molecular sieve separation of naphtha. The simplified approach with a pedigree matrix has been used for calculating the standard deviation.

Tab. 28.14 Unit process raw data for the molecular sieve separation of naphtha, RER

	Name	Location	InfrastructureProcess	Unit	naphtha, to molecular sieve separation	StandardDeviation95%	GeneralComment	hexane, at plant	heptane, at plant	fraction 1, from naphtha, at plant	2,3-dimethylbutan, from naphtha, at plant	2-methylpentane, from naphtha, at plant	methylcyclopentane, from naphtha, at plant	1,1-dimethylcyclopentane, from naphtha, at plant	methylcyclohexane, from naphtha, at plant	fraction 7, from naphtha, at plant	fraction 8, from naphtha, at plant
	Location				RER			RER	RER	RER	RER	RER	RER	RER	RER	RER	RER
	InfrastructureProcess				0			0	0	0	0	0	0	0	0	0	0
	Unit				kg			kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
allocated products	hexane, at plant	RER	0	kg	1.46E-1			100	0	0	0	0	0	0	0	0	0
products	heptane, at plant	RER	0	kg	1.42E-1			0	100	0	0	0	0	0	0	0	0
products	fraction 1, from naphtha, at plant	RER	0	kg	1.42E-2			0	0	100	0	0	0	0	0	0	0
products	2,3-dimethylbutan, from naphtha, at plant	RER	0	kg	9.71E-3			0	0	0	100	0	0	0	0	0	0
products	2-methylpentane, from naphtha, at plant	RER	0	kg	4.78E-2			0	0	0	0	100	0	0	0	0	0
products	methylcyclopentane, from naphtha, at plant	RER	0	kg	5.83E-2			0	0	0	0	0	100	0	0	0	0
products	1,1-dimethylcyclopentane, from naphtha, at plant	RER	0	kg	1.60E-2			0	0	0	0	0	0	100	0	0	0
products	methylcyclohexane, from naphtha, at plant	RER	0	kg	1.68E-1			0	0	0	0	0	0	0	100	0	0
products	fraction 7, from naphtha, at plant	RER	0	kg	8.44E-2			0	0	0	0	0	0	0	0	100	0
products	fraction 8, from naphtha, at plant	RER	0	kg	2.86E-1			0	0	0	0	0	0	0	0	0	100
resource, in water	Water, cooling, unspecified natural origin	-	-	m3	2.52E-2	1.08	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
technosphere	naphtha, at refinery	RER	0	kg	1.00E+0	1.08	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	transport, lorry 32t	RER	0	tkm	1.00E-1	2.09	(4,5,na,na,na,na); Standard distances 100km	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	transport, freight, rail	RER	0	tkm	6.00E-1	2.09	(4,5,na,na,na,na); Standard distances 600km	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	9.96E-6	1.08	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	heat, unspecific, in chemical plant	RER	0	MJ	3.11E+0	1.08	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	chemical plant, organics	RER	1	unit	4.00E-10	3.09	(4,5,na,na,na,na); Estimation	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
emission air, high population density	Heat, waste	-	-	MJ	3.59E-5	1.21	(4,2,1,3,1,1); Estimation	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	Carbon dioxide, fossil	-	-	kg	5.54E-2	1.21	(4,2,1,3,1,1); Estimation	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	Hexane	-	-	kg	1.68E-3	1.51	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	Heptane	-	-	kg	2.01E-3	1.51	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	Hydrocarbons, aliphatic, alkanes, cyclic	-	-	kg	1.03E-2	1.51	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	Hydrocarbons, unspecified	-	-	kg	1.40E-3	1.51	(2,2,1,3,1,1); Overcash 1998 - 2004	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
emission water, river	BOD5, Biological Oxygen Demand	-	-	kg	1.89E-2	1.51	(2,2,1,3,1,1); Calculated from water emissions	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	DOC, Dissolved Organic Carbon	-	-	kg	1.89E-2	1.51	(2,2,1,3,1,1); Calculated from water emissions	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	COD, Chemical Oxygen Demand	-	-	kg	4.74E-3	1.51	(2,2,1,3,1,1); Calculated from water emissions	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419
	TOC, Total Organic Carbon	-	-	kg	4.74E-3	1.51	(2,2,1,3,1,1); Calculated from water emissions	15.009	14.632	1.464	0.999	4.916	5.995	1.647	17.241	8.678	29.419

28.8 Cumulative Results and Interpretation

28.8.1 Introduction

Selected LCI results and values for the cumulative energy demand are presented and discussed in this chapter. Please note that only a small part of the about 1'000 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. It rather allows to show by examples the contributions of the different life cycle phases, or specific inputs from the technosphere to the selected elementary flows. Please refer to the ecoinvent database for the complete LCIs.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. Please use the data downloaded from the database for your own calculations, also because of possible minor deviations between the presented results and the database due to corrections and changes in background data used as inputs in the dataset of interest.

The ecoinvent database also contains life cycle impact assessment results. Assumptions and interpretations were necessary to match current LCIA methods with the ecoinvent inventory results. They are described in Frischknecht 2004. It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

28.8.2 Molecular sieve separation of naphtha

Tab. 28.15 shows selected LCI results and the cumulative energy demand for the molecular sieve separation of naphtha. The relevant factor is the energy demand for the process. Because the co-products are allocated by weight all co-products have the same values for selected results.

Tab. 28.15 Selected LCI results and the cumulative energy demand for the products of the molecular sieve separation of naphtha

		Name		1,1-dimethylcyclopentane, from naphtha, at plant	2,3-dimethylbutan, from naphtha, at plant	2-methylpentane, from naphtha, at plant	fraction 1, from naphtha, at plant	fraction 7, from naphtha, at plant	fraction 8, from naphtha, at plant	heptane, at plant	methylcyclohexane, from naphtha, at plant	methylcyclopentane, from naphtha, at plant	hexane, at plant
		Location		RER	RER	RER	RER	RER	RER	RER	RER	RER	RER
		Unit	Unit	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0	0	0	0	0	0
LCIA results													
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	59.4	59.4	59.4	59.4	59.4	59.4	59.4	59.4	59.4	59.4
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
LCI results													
resource	Land occupation	total	m2a	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2	4.4E-2
air	Carbon dioxide, fossil	total	kg	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1	8.1E-1
air	NMVOC	total	kg	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2	1.6E-2
air	Nitrogen oxides	total	kg	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3	2.3E-3
air	Sulphur dioxide	total	kg	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3	5.5E-3
air	Particulates, < 2.5 um	total	kg	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4	2.2E-4
water	BOD	total	kg	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2	3.5E-2
soil	Cadmium	total	kg	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10	7.4E-10
Further LCI results													
air	Carbon dioxide, biogenic	total	kg	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3	-1.1E-3
air	Methane, biogenic	total	kg	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6	1.3E-6
air	Carbon monoxide, biogenic	total	kg	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5	1.8E-5

Appendix: EcoSpold Meta Information

Type	ID	Field name, IndexNumber	3439
ReferenceFunction	401	Name	naphtha, to molecular sieve separation
Geography	662	Location	RER
ReferenceFunctic	493	InfrastructureProcess	0
ReferenceFunctic	403	Unit	kg
DataSetInformatic	201	Type	5
	202	Version	1.0
	203	energyValues	0
	205	LanguageCode	en
	206	LocalLanguageCode	de
DataEntryBy	302	Person	24
	304	QualityNetwork	1
ReferenceFunctic	400	DataSetRelatesToProduct	1
	402	IncludedProcesses	Molecular sieve separation of naphta including materials, energy uses, infrastructure and emissions.
	404	Amount	1
	490	LocalName	Naphtha, in Molekularsiebtrennverfahren
	491	Synonyms	
	492	GeneralComment	The multioutput-process "naphta, to melecular sieve separations" delivers the co-products hexane, heptane, 2,3-dimethylbutane, 2-methylpentane, methylcyclopentane, 1,1-dimethylcyclopentane, methylcyclohexane, fraction 1 from naphta, fraction 7 from naphta, and fraction 8 from naphta. The allocation is based on mass balance.
	494	InfrastructureIncluded	1
	495	Category	chemicals
	496	SubCategory	organics
	497	LocalCategory	Chemikalien
	498	LocalSubCategory	Organisch
	499	Formula	
	501	StatisticalClassification	
	502	CASNumber	
TimePeriod	601	StartDate	1998
	602	EndDate	2004
	603	DataValidForEntirePeriod	1
	611	OtherPeriodText	Time of publications.
Geography	663	Text	The inventory is modelled with data from plants in the USA.
Technology	692	Text	Separation of naphta with a zeolith 5a molecular sieve.
Representativene	722	Percent	0
	724	ProductionVolume	na
	725	SamplingProcedure	Literature data
	726	Extrapolations	Some data are derived from other or unknown plants or have been estimated.
	727	UncertaintyAdjustments	none
DataGeneratorAn	751	Person	24
	756	DataPublishedIn	2
	757	ReferenceToPublishedSource	40
	758	Copyright	1
	759	AccessRestrictedTo	0
	760	CompanyCode	
	761	CountryCode	
	762	PageNumbers	naphta
Länge 724			OK

References

Bhattacharjee 2005	Bhattacharjee, S.: Properties of some common fuels and hydrocarbons. Retrieved 17.3.2005 from http://kahuna.sdsu.edu/testcenter/testhome/Test/solve/basics/tables/tablesComb/hhv.html
Frischknecht 2003	Frischknecht R., Jungbluth N., Althaus H.-J., Hischier R., Spielmann M., Nemecek T., Hellweg S. and Dones R. (2003) Overview and Methodology. Final report ecoinvent 2000 No. 1. ESU-services, Uster, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, Online-Version under: www.ecoinvent.ch.
Frischknecht 2004	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Overcash 1998-2004	Overcash, M., Chemical life cycle database, Chemical and Biomolecular Engineering, North Carolina State University, Raleigh, NC 27695-7905. 1998 - 2004
Ruthven 2004	Ruthven, D. M.: Adsorption (Chemical engineering. In: Encyclopedia of physical science and technology (ed. Meyers, R. A.). Ramtech Limited, Tarzana, California 2004. Online-Version under: http://www.sciencedirect.com/
Ullmann 2004	Griesbaum, K., Behr, A., Biedenkapp, D., Voges, H.-W., Garbe, D., Paetz, C., Collin, G. Mayer, D., Hök, H.: Hydrocarbons. In: Ullmann's Encyclopedia of Industrial Chemistry, Seventh Edition, 2004 Electronic Release (ed. Fiedler E., Grossmann G., Kersebohm D., Weiss G. and Witte C.). 7 th Electronic Release Edition. Wiley InterScience, New York, Online-Version under: http://www.mrw.interscience.wiley.com/ueic/articles/a13_227/
UOP 2004	Catalysts and Advanced materials: ADS-34TM Adsorbent. UOP LLC. Retrieved 16.11.2004 from http://www.uop.com
Zhengzhou 2004	Zhengzhou Gold Mountain Science and Technique Co. Ltd.: Molecular sieve zeolith. Retrieved 11.11.2004 from http://adsorbentcn.com/Molecular%20sieve%20zeolite.htm