Swiss Centre for Life Cycle Inventories

A joint initiative of the ETH domain and Swiss Federal Offices

Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries

Data v2.0 (2007)

Roberto Dones, Christian Bauer, Rita Bolliger, Bastian Burger, Thomas Heck, Alexander Röder
Paul Scherrer Institut, Villigen

Mireille Faist Emmenegger, Rolf Frischknecht, Niels Jungbluth, Matthias Tuchschmid
ESU-services Ltd., Uster

ecoinvent report No. 5

Villigen and Uster, December 2007

Project "ecoinvent data v2.0"

Commissioners:	Swiss Centre for Life Cycle Inventories, Dübendorf Swiss Federal Office for the Environment (BAFU - FOEN), Bern Swiss Federal Office for Energy (BFE), Bern Swiss Federal Office for Agriculture (BLW), Bern
ecoinvent Board:	Alexander Wokaun (Chair) PSI, Villigen Gérard Gaillard, Agroscope Reckenholz-Tänikon Research Station, ART, Zürich Lorenz Hilty, Empa, St. Gallen Konrad Hungerbühler, ETHZ, Zürich François Maréchal, EPFL, Lausanne
ecoinvent Advisory Council:	Norbert Egli, BAFU, Bern Mark Goedkoop, PRé Consultants B.V. Patrick Hofstetter, WWF, Zürich Roland Högger, öbu / Geberit AG, Rapperswil Christoph Rentsch, BAFU (until January 2006) Mark Zimmermann, BFE (until July 2007)
Institutes of the ecoinvent Centre:	Swiss Federal Institute of Technology Zürich (ETHZ) Swiss Federal Institute of Technology Lausanne (EPFL) Paul Scherrer Institute (PSI) Swiss Federal Laboratories for Materials Testing and Research (Empa) Agroscope Reckenholz-Tänikon Research Station (ART)
Participating consultants:	Basler & Hofmann, Zürich Bau- und Umweltchemie, Zürich Carbotech AG, Basel Chudacoff Oekoscience, Zürich Doka Life Cycle Assessments, Zürich Dr. Werner Environment & Development, Zürich Ecointesys - Life Cycle Systems Sarl. ENERS Energy Concept, Lausanne ESU-services Ltd., Uster Infras AG, Bern
Software Support:	ifu Hamburg GmbH
Project leader:	Rolf Frischknecht, ecoinvent Centre, Empa, Dübendorf
Marketing and Sales:	Annette Köhler, ecoinvent Centre, Empa, Dübendorf

Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries (2004)

Editor (2004):	**Roberto Dones**
Authors (2004):	
Oil:	Niels Jungbluth, ESU-services
Natural Gas	Mireile Faist Emmenegger and Niels Jungbluth, ESU-services Ltd., Thomas Heck, PSI
Coal:	Roberto Dones, Christian Bauer, PSI
Nuclear:	Roberto Dones, PSI
Hydro Power:	Christian Bauer and Rita Bolliger, PSI
Wood Energy:	Christian Bauer, PSI
Heat Pumps:	Thomas Heck, PSI
Solar Collector Systems:	Niels Jungbluth, ESU-services Ltd.
Photovoltaic:	Niels Jungbluth, ESU-services Ltd.
Wind Power:	Christian Bauer and Bastian Burger, PSI
Combined Heat & Power:	Thomas Heck, PSI
Electricity Mix:	Rolf Frischknecht, ESU-services
Electricity Network:	Mireille Faist Emmenegger, ESU-services Ltd.

Contact address:

ecoinvent Centre
Empa
P.O. Box
CH-8600 Dübendorf
http://www.ecoinvent.org/
frischknecht@ecoinvent.org

Citation:

Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N., Röder A., Tuchschmid M. (2007) Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries. ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

Table of content

1 Summary

The whole report has not been updated to ecoinvent data v2.0. The results in its single chapters reflect ecoinvent data v1.1. The following text is from the previous versions. The reader is highly recommended to read the single energy systems reports updated to ecoinvent data v2.0 and use LCI data and results from the ecoinvent database.

The fossil, nuclear, and renewable energy systems included in ecoinvent Data v1.1 describe the situation around year 2000 of Swiss and European power plants and (where applicable) heating systems with the associated energy chains.

Comprehensive life cycle inventories of the energy systems have been updated and extended from the previous edition of the study (1996) and cumulative results calculated within the ecoinvent database framework. The work has been supported by the Swiss Office of Energy (BfE). Uncertainties have been estimated quantitatively for all input data, but they are not addressed here.

This report is intended as an introduction to the modelling of the energy systems and includes only a limited selection of results. Complete information is available in the German reports and in the database. Each energy system is concisely described in the following under a separate title.

Oil

The inventories of the oil energy system describe the production of oil products like petrol and naphtha for energetic and non-energetic uses. Furthermore, inventories for the production of thermal energy and electricity in Switzerland and different European countries have been elaborated. The process data for oil products include oil field exploration, crude oil production, long distance transportation, oil refining, regional distribution, and the use of oil products in boilers for space heating and industry as well as in power plants. For all these steps, air- and waterborne pollutants, production wastes as well as requirements of energy and working material have been inventoried. Relevant production facilities and the infrastructure have been considered. As far as possible and necessary, specific inventories for individual countries have been established.

The assessment shows that cumulative emissions of air pollutants are quite often dominated by the direct emissions from the combustion process. Nevertheless the delivery of the fuel causes important elementary flows to water and soil as well as resource uses, e.g. land occupation or fossil energy resources and can not be disregarded. Regional differences might be quite relevant and shall be considered while using inventory data and interpreting the results. The inventories for oil production, products and combustion can be considered as representative for these stages for the supply situation in Switzerland and Europe in the year 2000.

Natural Gas

The system model “Natural Gas” describes the production, distribution and combustion of natural gas for industrial and domestic applications in Switzerland and Western Europe. The inventory datasets for natural gas include gas field exploration, natural gas production, natural gas purification, long distance transport, regional distribution and combustion in boilers and power plants. The inventories consider the situation in Europe and Switzerland for the year 2000.

As far as possible and necessary, specific inventories have been investigated for single countries. The main producer countries for the supply of natural gas in Western European and Switzerland are the Russian Federation, The Netherlands, Norway, Germany, Great Britain, and Algeria. Their shares of the supply in different countries are considered. The import structure is decisive for the gas transport distances and for the environmental burdens related to the upstream chain. Onshore production has been treated separately from offshore production in case it was applicable and necessary for a region.

In order to represent current electricity production in Europe, average installed natural gas and industrial gas power plants have been considered. For the modelling of average plants in different countries and different regions, national average efficiencies are used. Large combined heat and power plants fuelled by natural gas have been considered as well in the current average electricity supply, as

far as data were available. Additionally, a dataset for the most advanced natural gas combined cycle technology currently available on the market has been included. For natural gas heating systems, boilers with advanced technology available on the market around year 2000 have been modelled.

Besides natural gas power plants, industrial gas power plants are described in separate datasets. Industrial gases include coke oven gas and blast furnace gas. Coke oven gas is a co-product of coke making; blast furnace gas is a by-product of steel production.

An important share of the resulting cumulative environmental burdens is generated by the production and processing of natural gas. Emissions per kWh electricity are distributed very differently over the chain for different species (e.g. CO_2, NO_x, CH_4). Carbon dioxide emissions are mainly the direct emissions during the operation of the power plant. For carbon monoxide, the emissions during production and transport are dominating. The direct emissions during power plant operation of a modern combined cycle power plant are relatively low. Cumulative methane emissions of a gas power plant originate almost completely from the upstream part of the chain. In particular the natural gas losses due to leakages in the long distance transport from Russia to UCTE countries are significant for the cumulative methane emissions. The distribution of the gas through the low pressure network contributes significantly to cumulative methane emissions.

Coal

Coal still plays an important role in the European electricity mix. Hard coal has been analysed separately from lignite. Lignite mining is addressed only for average European conditions. The analysed products are raw lignite, lignite dust and briquettes. Heat production is considered for a briquette stove with 5-15 kW thermal capacity. Key parameters for a high number of single lignite power plants in Europe have been used for determining country-specific average power plants as well as average UCTE and CENTREL lignite plant mixes. Considering the huge fuel masses to be burned, lignite power plants are mine-mouth. Therefore, the lignite energy chain is modelled without coal transport between mining and power plant.

Hard coal mining is addressed for eight important production regions in the world: Eastern and Western Europe, North and South America, South Africa, East Asia, Russia, and Australia. Key parameters for a high number of single hard coal power plants in Europe around year 2000 have been used for determining country-specific hard coal electricity production as well average UCTE and CENTREL hard coal plant mixes. For each of these countries, a specific hard coal supply mix has been defined, representing the import shares from the eight production regions in year 2000. Due to limited data, steam coal is not treated separately from other mine products in the datasets describing the mining step in the eight regions. However, production of hard coal briquettes and coke making following mining is separately addressed. Coking is modelled for German and average worldwide conditions. Heat systems are represented by a 5-15 kW stove and a 1-10 MW industrial furnace, fired with different coal products. The modelled heating systems reflect average European condition in the middle of the 1990s.

The current data for hard coal and lignite power plants are rather complete. Actual operation data for most of coal power plants (nearly 700) in the mentioned countries have been collected and processed.

In general, there are substantial differences for country-specific results for both hard coal and lignite chains. For direct power plant air emissions, emissions mostly depend on the efficiency of the plants as well as on the installation rate and efficiency of emission control devices. Whereas the upstream chain of lignite power plants does not have a significant influence on the cumulative results, the upstream chain of hard coal power plants can be considered an important factor, especially for countries importing oversea coal. The transport from these production regions to Europe generates for example relatively high emissions of nitrogen oxides and particulates.

Within the modelled heating systems, heat production with briquettes and coke gives higher cumulative emissions than heating with anthracite and industrial coal, because the energy requirements and direct emissions during processing of the raw coal play an important role. Similarly to electricity production at hard coal power plants, mining and transport may significantly contribute to the cumulative results of heating systems.

Long-term emissions to water from leaching during mining and coal processing could not be modelled.

Nuclear

The nuclear cycles associated with power generation at Light Water Reactors (LWR) currently installed in Western Europe, with focus on the Swiss Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) of the 1000 MW class and with Swiss conditions for spent fuel management have been modelled. Compared to the previous editions of this study, besides use of enriched uranium originating from natural uranium ore, recycling of plutonium from reprocessing and of depleted uranium from enrichment in mixed-oxide (MOX) fuel, recycling of uranium from spent fuel mixed with highly enriched uranium from dismantled warheads to make RepU fuel elements, have been modelled where applicable using a static approach (plutonium at equilibrium). The plutonium and the depleted uranium are not loaded with the environmental burdens from the steps producing them. However, all cumulative burdens from reprocessing are attributed to the processed spent fuel and all cumulative burdens from the enrichment step are attributed to the production of enriched uranium. The modeling here proposed considers RepU fuel as if it were using uranium from natural sources, i.e. as if it were enriched for direct use for civil purposes.

Modelling of uranium mining includes open pit and underground mining but no chemical extraction. Long-term emission of radon from uranium milling tailings have been estimated considering average conditions worldwide; conversely, long-term emissions into groundwater have not been estimated. Two commercial enrichment processes, diffusion and centrifuge, have been modelled each with two different facilities to take into account the great variability in energy intensity and type of supply of electricity. Detailed data on the infrastructure of the modelled Swiss PWR and BWR have been extrapolated to French, German, and average UCTE conditions. Specific data on average burn-up, load factor, fraction of spent fuel to reprocess over the lifetime, as well as radioactive emissions to air and water for all modelled power plants were available. The amounts and waste management of radioactive waste from operation and decommissioning of power plants are based on Swiss data from the 1990s. Current radioactive and non-radioactive emissions from the reprocessing facility in La Hague have been used. A simplified model of conditioning of spent fuel by encapsulation without reprocessing has been developed. The waste products from reprocessing and the conditioned radioactive waste from the operation of power plants are transported to the Swiss Interim Storage. The new concept for a partially reversible Swiss geological final repository of high and intermediate long-lived radioactive waste (H-ILW) in opalinus clay has been modelled, using the waste inventory for the current policy for recycling 40% of the total Swiss spent fuel over a lifetime of 40 years for the operating five power plants. The geological final repository for low and medium short-lived radioactive waste (LLW) is based on data from the concept developed in mid 1980s, for lack of more recent data.

Compared to the previous edition of this study, emissions from combustion, including greenhouse gases, have decreased due to the decreasing share of the enrichment services from the US diffusion facilities (only one has remained operational) supplied by coal power plants, and the decrease of utilization rate of natural uranium due to recycling of plutonium in MOX. Radon is released to air from mining and milling, where the predominant part is the long term emissions from mill tailings. Noble gases originate from power plant and reprocessing; the emission of such noble gases from reprocessing per unit mass of heavy metal is nearly three orders of magnitude higher than for the unit mass of uranium in LWR fuel elements. The LWR and reprocessing are the major contributors to total release of aerosols. Typically, a BWR emits more aerosols than a PWR during operation.

The emissions of naturally occurring radium to water stem basically from mining and milling. The emissions of tritium und mixed nuclides originate prevalently from reprocessing, in smaller amounts from the power plant. The emissions (per kWh) of mixed nuclides from the fuel cycles associated with the Swiss PWR and BWR are one order of magnitude smaller than those from reprocessing. Typically higher tritium release per kWh to water from the Swiss PWR, and higher mixed nuclides release from the Swiss BWR are accounted for. The natural isotopes of uranium und thorium are predominantly released from mining and milling, whereas man-made isotopes of actinides originate from reprocessing. BWRs produce typically more LLW from operation and decommissioning than PWRs. Also the H-ILW volume is higher, due to the slightly higher mass of spent fuel per kWh.

Hydro Power

Main goal of the assessment of hydroelectric energy is the quantification of material and energy flows during installation and operation of Swiss average reservoir and run-of-river power plants, as well as pumped storage. European country-specific hydroelectric energy mixes of the two types and country-specific shares of pumped storage power are also included, but no specific data were available for non-Swiss units. Only Swiss concrete dams with a height of more than 30 meter are taken into account.

Requirements of most important materials – cement, gravel, steel, and explosives – during the construction of power plants are taken into account, as well as energy requirements, particle emissions, and transports. Land use, requirements of lubricating oil, and greenhouse gas emissions from the surface of reservoirs during operation are quantified as well. However, no analysis of net greenhouse gas emissions from the entire catchment area and considering full lifetime has been performed.

Cumulative results of the inventory for electricity production at the modelled hydropower plants are dominated by material and energy requirements during construction. Lifetime and expected annual electricity production assumed for the normalization of the construction inventories of all hydropower datasets represent Swiss conditions, although in reality they could differ for other regions.

Wood Energy

Several classes of wood heating systems have been modelled, which represent average technologies available on the central European market around year 2000: wood chip fired 50 kW, 300 kW, and 1000 kW boilers; wood log fired 6 kW, 30 kW, and 100 kW boilers; and, pellet fired 15 kW and 50 kW boilers. Hardwood, softwood, and mixed wood (72% softwood and 28% hardwood, representing the Swiss commercial wood mix) directly from forest are assumed to be burned at log boilers; hardwood, softwood, and mixed wood directly from forest or residues from wood industry are assumed to be burned at chip furnaces. In general, wood log boilers have lower efficiencies than wood chips and pellets furnaces of comparable capacity. Pellets boilers have slightly higher efficiencies than wood chips furnaces of similar capacity.

Two cogeneration plants installed in Switzerland have been analysed. They have installed thermal capacity of 6400 kW_{th} and 1400 kW_{th}, and power rate of 400 kW_{el} and 335 kW_{el}, respectively. Both plants have also been modelled hypothesizing the installation of a baghouse filter and a Selective Non Catalytic Reduction (SNCR) de-NO_x system instead of the currently used multi-cyclone. Mixed industrial chips are used as fuel. Allocation to heat, energy, and exergy is modelled for all four datasets.

No waste wood is considered for the production of firewood in this study, but only untreated wood. The upstream chain from the growth of the trees through the wood fuel preparation has been addressed in (Werner et al. 2003). Only the transport of firewood to consumers, and the infrastructure and operation of the heating systems and cogeneration plants are addressed here. Energy losses due to heat distribution are outside the boundaries of the systems.

The analysis of the wood chain shows that direct emissions from wood burning are generally dominating cumulative air emissions. On the other hand, burdens not originating from wood combustion mostly come from wood fuel production and transport. Total air emissions from heat production at pellet boilers are smaller than from chip and log boilers, in spite of the higher energy consumption for pellet manufacturing.

The differences between the combustion of hardwood and softwood are small. Due to the higher nitrogen content, hardwood heating systems have 25% higher direct NO_x emissions. Pellet boilers emit lower NO_x than other wood boilers. The reason is that pellets are often prepared without using the bark, which has higher nitrogen content than wood.

Using economic criteria, Werner et al. (2003) allocate almost all burdens from the wood industry to wood products rather than to wood residues, from which industrial chips are made. The consequence is that the contributions of the upstream chain for the production of forest wood chips to cumulative results are higher than for industrial chips.

For cogeneration the influence of the modelled emission control is very important for the cumulative emissions of the controlled species. On the other hand, the assumed differences in material requirements and the reduction in electric efficiencies due to the hypothesized installation of a baghouse filter and an SNCR device do not have important consequences on cumulative results. The only exception is higher emission of N_2O due to the use of urea in the SNCR.

The electric efficiencies of the modelled cogeneration plants are rather small because they are designed and operated mostly for heat production. Electricity is more or less a byproduct and is mostly used within the plants. Therefore, the cumulative results of electricity production at these plants should not be used for comparison with other electricity systems.

Heat Pumps

Two wide-spread types of heat pumps are modelled: an air/water heat pump and a brine/water heat pump. For both types of heat pumps a low temperature hydronic floor heating system was assumed for the distribution of heat within the house. For modelling, 10 kW heat pumps for one-family houses are assumed. Datasets are provided both for heat at heat pump before heat distribution and for heat at radiator after heat distribution. Two locations are considered: Switzerland and average Europe. Significant differences in cumulative results due to the different natural heat reservoirs and different electricity supply have been identified. For total cumulative greenhouse gas emissions from a heat pump with refrigerant R134a, the emissions of the refrigerant are relatively significant for the cumulative amounts.

Solar Collector Systems

The model of solar collector systems describes the direct use of solar energy for warm water supply and heating for one-family houses and multiple dwellings in Switzerland. Two different types (flat plate and glass tube) of solar collectors used in Switzerland are distinguished. All systems are equipped with an additional heating system to compensate insufficient production in periods of cloudy weather. Process data are simulated for two cases: pure solar heat and combined solar heating. For the pure solar heat case the additional heating is excluded from the analysis. Thus environmental burdens are shown solely for the solar collector. The process data include production of construction materials, manufacturing (and dismantling after end of life) of collectors, storage tanks, piping, circulation pumps, heat exchanger, and coolant as well as installation and operation of the system for 25 years.

Important for the environmental burdens caused is the manufacturing of the collector and the additional components of the system. Major environmental burdens arise from the use of metals (copper and steel) for the construction. Also the operation phase, with the electricity use for pumps, is significant. The type of auxiliary heating, e.g. electric heating, gas or wood boiler, that is necessary for the system, is also a contribution that is quite important to the total environmental burdens. The inventory for solar collector systems describes certain case studies for these types of installation used in Switzerland. These examples are not representative for the market situation nor for the average installations of such systems. Thus these examples cannot be used as background data to assess the environmental burdens of a solar collector system. However, the database contains enough inventories for different components of such solar systems to model a particular situation in a practical example and for a given location.

Photovoltaic

The model of the photovoltaic energy system addresses the entire manufacturing process associated with the production of electricity with photovoltaic power plants newly installed in Switzerland.

Twelve different, small scale, 3 kWp grid-connected photovoltaic plants have been considered. Ten refer to the technology in year 2000, two are based on a near-future scenario using an improved production technology. They differ according to the cell type (mono- and polycrystalline, mc-Si and pc-Si, respectively), and the place of installation (slope roof, flat roof, and façade). Slope roof and façade systems are further distinguished according to the kind of installation (building integrated or mounted). The inventory for the production system is split up into several stages. These production stages take place in different European countries.

The inventory result for the production stages is quite dependent on the choice of location specific electricity mixes. The analysis shows that each production stage may contribute an important share to cumulative results for certain environmental flows. The energy pay-back-time, estimated with cumulative energy demand categorized separately for fossil, nuclear, and renewable energy, lies between 3 and 6 years for the different plants investigated for today situation, using a modern gas combined cycle power plant as the reference system. The life cycle inventories for photovoltaic power plants can be assumed to be representative for newly installed plants in Switzerland in the year 2000. Differences in the results due to the situation in other countries in comparison to the modelling for Switzerland are mainly due to different solar irradiations at different locations. Further on it should be considered that the inventory may not be valid for systems produced outside of Europe, because production technologies and power mixes for production processes might not be the same. A scenario for a future technology helps to assess the relative influence of technology improvements for some processes in the near future (2005-2010).

Wind Power

Life cycle inventories of electricity generation at wind power plants of 30 kW, 150 kW, 600 kW, and 800 kW are performed for Swiss conditions, the latest two using 14% capacity factor. The data of the 800 kW plant are also adapted to average European conditions, with 20% average capacity factor. Additionally, a 2 MW offshore wind power plant is assessed, based on information from the wind park Middelgrunden, DK, with 30% capacity factor rounding up the annual production to get a rough value for near to coast Northern European conditions.

The infrastructure is divided into two parts. The basement and the tower ("fixed parts"), with an assumed lifetime of 40 years for onshore plants and 20 years for the offshore plant; the moving parts (rotor, nacelle), the electric and electronic components ("moving parts"). A lifetime of 20 years is assumed for the latter as well as for the copper cable connecting the turbine to the electric grid.

The key factors for the cumulative results of the inventory are the capacity factor of the plants, the lifetime of its parts, and the rated power; the higher these factors, the lower the total burdens of onshore electricity production. However, this scaling effect cannot be applied to extrapolate from onshore to offshore plants. When comparing the cumulative burdens of the 800 kW onshore with the 2 MW offshore turbines for average European conditions, the beneficial effects of increasing capacity and higher wind speed are overcompensated by the more complex construction and installation of the offshore plant, besides the assumption of only 20 years lifetime for all its components. That is why, the environmental performance of the offshore turbine is worse for the analysed conditions, but this could be different at other sites.

The analysis of results also shows that most of the elementary flows are dominated by the material use: steel for the tower, the basement, and the nacelle; concrete for the basement; and, glass fibre reinforced plastics for the rotor blades. The contribution from the transport of materials, assembling and installation, as well as waste disposal are nearly negligible for most of the burdens in the case of onshore turbines, whereas the installation work contributes discernibly to the total burden of the offshore plant.

Combined Heat & Power

Different types of small natural gas combined heat and power (CHP) plants are described. A 200 kW_e diesel CHP plant is modelled as well. The natural gas plants have capacities between 2 and 1000 kW_e. Natural gas lean burn and lambda1 motors have been considered. The lambda1 motor implies a three-way catalytic converter. The lean burn CHP plants are operated (and modelled) without catalysts. For the diesel CHP, an SCR (Selective Catalytic Reduction) catalyst and an oxidation catalyst have been considered. The requirements for infrastructure of CHP components have been inventoried in detail. For most of the datasets it was assumed that the CHP plant is operating in Switzerland. A dataset of a 1 MW_e natural gas plant located in Europe is included as well.

The natural gas combined heat and power plants have lower cumulative carbon dioxide emissions and NO_x emissions than the modelled diesel plant. Natural gas CHP units with three-way catalysts have the lowest cumulative nitrogen oxide emissions, although the technology with catalyst increases slightly the nitrogen oxide emissions from the rest of the chain. The results per kWh electricity or per MJ heat depend significantly on the allocation method. Therefore, several alternatives of allocation are offered in the database for each CHP plant.

Electricity Mixes and Electricity Network

In ecoinvent Data v1.1 the electricity production, transmission and supply of the following Organizations and countries are modelled:

UCTE: Belgium, Germany, Spain, France, Greece, Slovenia, Croatia, Bosnia Herzegovina, Serbia and Montenegro, Macedonia, Luxembourg, the Netherlands, Portugal, and Switzerland;

CENTREL: Czech Republic, Hungary, Poland, and Slovak Republic;

NORDEL: Denmark, Finland, Norway, and Sweden (Iceland, the fifth NORDEL-country is not considered);

United Kingdom and Ireland.

Two kinds of electricity mixes are distinguished, namely the domestic production mix (called "production mix") and the mix including electricity trade among countries (called "supply mix").

The mixes are based on the yearly production in the year 2000. The following average technologies are discerned: hard coal, lignite, fuel oil, natural gas, industrial gases (coke oven gas and blast furnace gas), hydroelectric power (run-of-river and storage), pumped storage, nuclear power (pressurised and boiling water reactors), wind power (on- and offshore), photovoltaics, biomass (wood co-generation), and others. It is assumed that the electricity produced in waste incineration facilities (included in "others") does not bear any environmental loads. The properties of the different technologies, their resource consumption and emissions are reported in the respective parts of this report.

Four voltage levels are distinguished, namely at the busbar of power plants, and at high, medium and low voltage level in the grid. Distribution losses and infrastructure intensity vary considerably among the different voltage levels.

The cumulative emissions per kWh_e of country mixes vary considerably according to the shares of power plant technologies used (fossil, nuclear, hydropower). The specific CO_2 emissions vary between 9 g and 1100 g per kWh (Norway and Poland, respectively), reflecting the share of fossil in the supply mix. Specific total Radon-222 emissions (short and long-term) vary between 3 and 600 kBq per kWh_e (Norway and France, respectively), reflecting the share of nuclear power in the supply mix. The Swiss supply mix causes the emissions of 110 g CO_2 and 340 kBq Radon-222 per kWh_e. The emissions increase to 120 and 130 g CO_2 per kWh_e, and to 350 and 380 kBq Radon-222 per kWh_e for the Swiss medium and low voltage electricity mix, respectively. The cumulative SO_2 emissions of the UCTE-mix 2000 (1800 mg/kWh_e) are nearly 40 % lower than the emissions of the UCPTE-mix 1990-1994 (reported in the 1996 LCI data on energy systems). Cumulative NO_X emissions did not change since then and amount to 830 mg per kWh_e for the UCTE-mix 2000. The results of the CENTREL- and NORDEL-mix are influenced by a large share of fossil power and a large share of hydroelectric and nuclear power, respectively.

SF_6-emissions of switching stations and the heavy metals leaching from wooden poles in the grid are considered. Large differences are observed in terms of SF_6-emissions and losses in the country-specific transmission and distribution networks.

2 Introduction and Goal

2.1 Background

In 1994 the first edition of the Swiss Life Cycle Inventory (LCI) study on current Swiss and Western European energy systems was issued (Frischknecht et al. 1994). It covered all main energy chains associated with installed electricity and heating technologies, with focus on the Swiss and Western European situation. Electricity mixes were addressed for UCTE countries.[1] The work was updated and extended with the third edition published in 1996 (Frischknecht et al. 1996). In both editions, different industrial sectors linked with the energy systems, like transport, construction machines, material manufacturing, and waste treatment were modelled with sufficient detail for serving the assessment of cumulative burdens associated with the unit of electric energy or heating energy delivered by any energy system. The Swiss LCI study was the first to use standard and internally consistent rules for assessing all systems as well as an algorithm for calculating all recursive contributions and feedbacks.

With the increasing interest and uses of the LCA methodology, several other specific studies and specialized databases have flourished in Switzerland and elsewhere for different economy sectors. Therefore, it became more and more apparent that each of them can profit from putting all them together in a consistent and unifying database system. The database on energy systems mentioned above offered a suitable starting point framework for such an endeavour.

The Swiss project "ecoinvent 2000" started in year 2000 and was completed in 2003, and its follow-up project "ecoinvent Introduction" terminated in mid 2004. The Organizations of the ETH-Domain EAWAG, EMPA (St. Gallen and Dübendorf), EPFL, ETHZ, and PSI, as well as the Swiss Federal Research Station for Agroecology and Agriculture (Agroscope FAL Reckenholz) joined and founded the ecoinvent Centre, or Swiss Centre for Life Cycle Inventories.[2] They received support from several Swiss Federal Offices. In particular, the work on the energy systems herewith addressed has been funded by the Swiss Office of Energy (BfE).

This report presents in concise form the results obtained with these projects. The results are included in ecoinvent Data v1.1 released in July 2004.

2.2 Goal of the ecoinvent 2000 project

The aim of the project "ecoinvent 2000" was to create the ecoinvent database, to establish a suitable data format (EcoSpold), to make all existing databases consistent when transferred into ecoinvent, to update all inventory data to year 2000, and to extend the modelling to more processes and products. The sectors included besides the energy systems are: construction materials, metals, chemicals, paper and board, forestry, agriculture, detergents, transport services and waste treatment. . Full information on the ecoinvent projects is available in (Frischknecht et al. 2004), while specific information on LCI for different sectors is available in individual reports of the ecoinvent series.

Complying with the general goals of ecoinvent, the addressed fossil, nuclear, and renewable energy systems describe the situation around year 2000 of Swiss and European power plants and heating systems with the associated energy chains. Besides UCTE systems, also electricity systems operating in CENTREL and NORDEL countries have been addressed, although with limited degree of details compared to UCTE ones. For all economy sectors, more than 2500 individual processes have been modelled in ecoinvent using full process analysis. About half of the datasets are energy-related. Comprehensive life cycle inventories of the following energy systems were established and cumulative results calculated within the ecoinvent database framework:

---

[1] By that time it was called UCPTE (Union for the Coordination of the Production and Transport of Electricity).

[2] http://www.ecoinvent.ch

- Oil
- Natural gas and industrial gases
- Coal – hard coal and lignite
- Nuclear
- Hydro power
- Wood energy
- Heat pumps
- Solar collector systems
- Photovoltaic
- Wind power
- Combined heat & power (natural gas and diesel oil)
- Electricity mix and electricity network

Uncertainties have been estimated quantitatively for all single input values. The uncertainty factors, provided in the database as well, are the basis for the calculation of uncertainties of the cumulative results for each elementary flow. In this report, the uncertainties of the input data are neither presented nor discussed, but an illustrative example is shown in the natural gas chapter.

This report has been designed to provide a comprehensive introduction in English language to the modelled energy systems and the results included in the ecoinvent Data v1.1. However, complete information on the energy systems, on the model data, and further analyses of results are available in the large German report (Dones et al. 2004), where all chapters but the one on electricity mixes hold the same sequencial numbering. Complete input data and results are accessible in the database. The reader who wishes to get deeper into specific subjects is invited to dig them out from the German report and the database.

Each energy system is concisely described in the following under a separate chapter. Responsibility of the modelling for each system lies with the authors of the corresponding chapter. However, readers and users are invited to acquire from the available information the level they need for appropriate understanding before using the inventories into own applications.

2.3 References

Dones et al. 2004 — Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N. and Röder A. (2004) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent 2000 No. 6. 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., Hischier R., Hellweg S., Nemecek T., Rebitzer G. and Spielmann M. (2004) 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. 1996 — Frischknecht R., Bollens U., Bosshart S., Ciot M., Ciseri L., Doka G., Dones R., Gantner U., Hischier R. and Martin A. (1996) Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut, Villigen, Bundesamt für Energie (Hrsg.), Bern, CH, retrieved from www.energieforschung.ch.

Frischknecht et al. 1994 — Frischknecht R., Hofstetter P., Knoepfel I., Dones R. and Zollinger E. (1994) Ökoinventare für Energiesysteme. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 1. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut Villigen, Bundesamt für Energie (Hrsg.), Bern.

3 Methodology

3.1 General ecoinvent methodology

The methodology used in ecoinvent, and consequently applied to the modelling and inventorying of energy systems, is extensively described in (Frischknecht et al. 2004a) and will not be reported here. A few energy-specific methodological issues are included in the German report (Dones et al. 2004). The ones necessary for interpreting some results (e.g. allocation) have been shortly discussed within specific chapters herein.

The chapters on individual energy systems in the German report together with the corresponding input datasets have been reviewed within the ecoinvent group by colleagues not directly involved in the assessment of energy systems. Additionally, internal review has been performed within the energy group all the way through the project. The chapters of this English report have only been reviewed internally.

3.2 Discussion of results

For each energy chain, selected LCI results and values for the cumulative energy demand are presented and discussed for representative energy carriers, electricity at busbar of power plants, and heat at boilers (where applicable). Only a small part of the about 1'000 elementary flows is presented here as well as in (Dones et al. 2004). 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 reader is invited to refer to the complete list of elementary flows and the total cumulative results for all chains directly in the ecoinvent database.

The shown selection is not suited for a life cycle assessment of the analysed processes and products. The user is invited to download the data from the database for 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. (2004b). It is strongly advised to read the respective chapters of the implementation report before applying LCIA results.

3.3 References

Dones et al. 2004	Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N. and Röder A. (2004) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent 2000 No. 6. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
Frischknecht et al. 2004a	Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hischier R., Hellweg S., 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., Hellweg S., Hischier R., Humbert S., Margni M., Nemecek T. and Spielmann M. (2004b) 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.

4 Oil

Author: Niels Jungbluth, ESU-services

4.1 Introduction

The inventories for the oil energy system describe the production of oil products like petrol and naphtha for energetic and non-energetic uses. Furthermore an inventory for the production of thermal energy and electricity in Switzerland and different European countries has been elaborated.

Fig. 4.1 shows an overview for the modelled chain. The process data for oil products include oil field exploration, crude oil production, long distance transportation, oil refining, regional distribution, and the use of oil products in boilers for space heating and industry as well as in power plants. For all these steps, air- and waterborne pollutants, production wastes as well as requirements of energy and working material have been inventoried. Relevant production facilities and the infrastructure have been considered. As far as possible and necessary, specific inventories for individual countries have been established. Transport services needed to supply energy and materials and treatment processes needed for the production wastes are included as well.

Dotted boxes in Fig. 4.1 indicate the products of multi-output processes. These processes have been inventoried per year (a) or per mass of input, and then the elementary flows have been allocated to these products (which are not all shown). Many process stages have been inventoried separately for different countries according to the supply situation relevant for Switzerland and Europe.

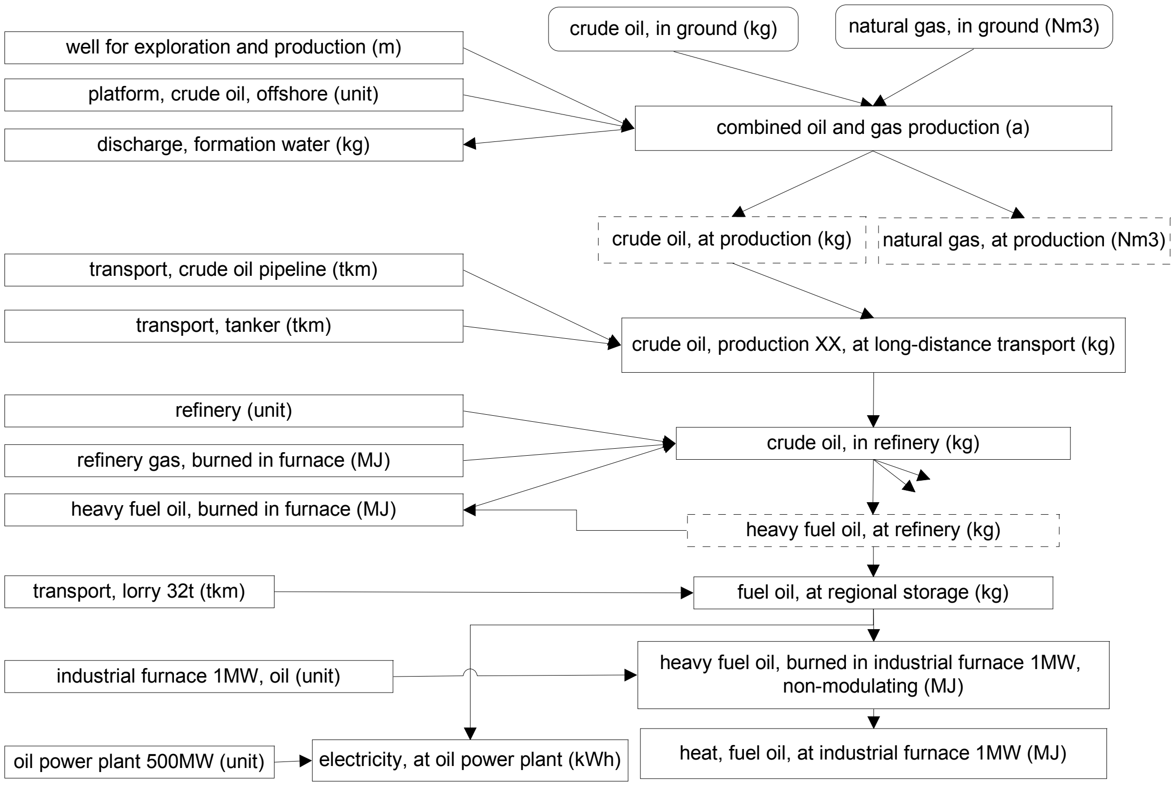

Fig. 4.1 Overview of the modelling of the oil production chain

4.2 Chemical and physical product properties

The oil products analysed, their heating value and composition are listed in Tab. 4.1.

Tab. 4.1 Chemical composition, heating values and density; figures per kg oil product.

		Petrol	Diesel	Kerosene	Light fuel oil	Heavy fuel oil used in boiler in CH	power plant /boiler RER	Marine bunkers
		kg	kg	kg	kg	kg	kg	kg
Main elements:								
C	kg	0.865	0.865	0.850	0.862	0.875	0.850	0.84
H	kg	0.135	0.133	0.150	0.134	0.105	0.11	0.10
O	kg	0.003	0	0	-	0.005	0.010	0.013
N	kg	-	0	0	0.00014	0.0045	0.0045	0.01
S	kg	0.00216	0.0035	0.0005	0.001	0.0084	0.015	0.035
Trace elements:								
Al	mg	-	-	-	-	-	-	7
As	mg	-	-	-	-	0.8	0.8	0.7
Ca	mg	-	-	-	-	7	5	6
Cd	mg	0.01	0.01	-	-	0	2	-
Cl	mg	-	-	-	4	90	90	-
Co	mg	-	-	-	-	2	2	0.43
Cr	mg	0.05	0.05	-	-	0.3	1	0.35
Cu	mg	1.7	1.7	-	0.03	1	3	0.4
F	mg	-	-	-	0.4	9	9	-
Fe	mg	-	-	-	-	50	11	13
Hg	mg	0.07	0.02	0.02	0.02	0.006	0.006	0.02
Mo	mg	-	-	-	-	0.5	1	0.56
Na	mg	-	-	-	-	46	46	35
Ni	mg	0.07	0.07	-	-	30	40	34
P	mg	-	-	-	-	-	-	4
Pb	mg	30	0.11	-	-	9	3.5	0.15
Se	mg	0.01	0.01	-	-	0.75	0.75	0.2
Si	mg	-	-	-	-	-	-	6
V	mg	-	-	-	-	60	160	89
Zn	mg	1	1	-	0.03	3.5	2.5	-
Heating values:								
H_l [1])	MJ	42.8	42.8	43.25	42.7	40.6	40.0	38.9
H_u [2])	MJ	45.8	45.5	46.0	45.4	43.0	42.3	41.2
Density	kg/l	0.75	0.84	0.795	0.84	0.95	1.0	-

-: no data

[1]): H_l: lower heating value (net calorific value),

[2]): H_u: upper heating value (gross calorific value)

4.3 System description

All subsystems shown in Fig. 4.1 are included as unit processes in the database. The analysis of the oil fuel chain in particular is divided into the process stages described in the following sections (Jungbluth 2004).

4.3.1 Oil field exploration

The material and energy uses as well as emissions caused by drilling activities are investigated for the inventory. The elementary flows caused by information technology required for geophysical prospection, are proven to be negligible (Frischknecht et al. 1996). Main issues are barite and bentonite consumption and the emission of oily drilling fluids into the sea, where large parts of the benthos is affected. Mainly, emission data for North Sea exploration are used.

4.3.2 Crude oil production

Tab. 4.2 shows the share of different regions for imports and exports of crude oil and oil products to Europe.

Tab. 4.2 Import and export of crude oil and oil products to and from Europe in year 2000 (BP Amoco 2001)

Million tonnes	Import	Share	Export
USA & Canada	10.7	2.1%	72.0
Mexico	10.1	2.0%	0.2
S. & Cent. America	12.3	2.5%	1.4
Former Soviet Union	124.0	24.9%	
Central Europe	3.2	0.6%	9.5
Middle East	182.7	36.6%	
North Africa	101.6	20.4%	
West Africa	27.6	5.5%	8.4
Asia Pacific	1.5	0.3%	9.8
Rest and Unidentified	25.0	5.0%	2.4
TOTAL	**498.7**	**100%**	**103.7**

Crude oil production is investigated for different regions as shown in Tab. 4.3. The variation in drilling efforts and energy consumption between different regions is modelled. For the major oil producing regions a distinction has been made between on- and offshore production based on the data available. Emissions to air and water from offshore activities are in some cases estimated with data from the North Sea. No sufficient inventory data were available for oil exploration and production in North-Africa and the Middle East. Data from activities in the North Sea or in Nigeria, respectively, are used to fill data gaps. The full details of the different inventories can be found in the final report (Jungbluth 2004).

The structure of available data for different countries is not directly comparable. Different types of information have been used to elaborate the inventories. This made it necessary to adapt the structure of the inventories to the availability of information. Thus inventory data for different regions shall not be compared among each other on the level of unit process raw data, but on the level of cumulative results (Tab. 4.7).

For flaring and venting of gases extracted together with crude oil, world-wide average data have been used if country specific data were not available. There are large differences for VOC and especially methane emissions depending on the possible variations in regional uses of the extracted gases. The allocation of the elementary flows between natural gas and crude oil for combined production is based on the lower heating values of the products. It has to be noted that a part of the production locations (Russia, the Netherlands and Norway) are modelled as a combined production within the inventories for natural gas production (Faist Emmenegger et al. 2003).

Tab. 4.3 Investigation of different regions for crude oil exploration

Region	Data sources and quality
North Sea (GB, NL, NO)	Environmental reports with summarized information for all oil fields, good quality.
Russia and Nigeria	Questionnaires with particular information for some suppliers, medium quality.
Middle East and Africa	Rough estimation based on some key information from literature.

Production processes of certain chemicals, especially the ones used in oil exploration and production, could not be analysed in detail. Although partly emitted to the sea, not all of these chemicals are considered as specific waterborne pollutants.

Thermal energy required in crude oil production is modelled assuming heavy fuel oil boilers although crude oil is often used in reality. Off-grid electricity required in exploration and production is provided by diesel engines and gas turbines.

Land use for exploration and production is based on literature data and scientific publications. For offshore oil production, the "land use" of the benthos, i.e. the sea ground of the continental shelf, is quantified based on investigations made in the North Sea. Drilling residues are directly disposed of and cover the benthos within an area of about 1 km diameter around the drilling site.

4.3.3 Long distance transportation

Distances for crude oil imports are investigated according to the specific supply situations for refineries in Switzerland and Europe. High sea and inland tanker, as well as onshore and offshore pipeline are considered as transportation means. Oil spills of cross country pipelines are included in the inventory. Pipelines occupy surfaces during construction and partly during operation. Land use figures are mainly based on assumptions and include the occupation of the benthos for offshore pipelines. Due to globalized and highly atomised markets, transport services cannot be modelled exactly. International and national statistics about imports and exports are used to approximate distances and transport means.

4.3.4 Oil refining

Oil refineries are complex facilities. Several processes, such as distillation, vacuum distillation, or steam reforming are required to produce a large variety of oil products such as petrol, light fuel oil or bitumen. All oil products sold in Europe are assumed to be refined in Europe. Oil products used in Switzerland are assumed to be a mix of domestic production and imports (see Jungbluth 2004 for details). The following products are investigated separately for Switzerland and Europe, unless otherwise noted:

- petrol (unleaded and two-stroke blend)
- diesel
- petroleum coke (only RER)
- fuel oil (heavy and light)
- kerosene
- naphtha
- sulphur
- electricity
- low-sulphur fuels[3]

Before executing allocation of the refinery process, the refinery has been divided as far as possible in sub processes (process units such as distillation or steam reforming). Since these sub processes are multifunction systems (the distillation units delivers several intermediate products from gaseous hydrocarbons to heavy, viscous residues), allocation cannot be fully avoided. In such cases, mass is

[3] Rough estimation of additional energy requirements.

used as an arbitrary parameter because no economic information about intermediate products is available and heating values do not differ that much (Frischknecht et al. 1996).

As an example, the allocation factors used for energy inputs are shown in Tab. 4.4. All other inputs and outputs to the refinery are considered with specific allocation factors which are documented in the final report (Jungbluth 2004).

Tab. 4.4 Factors for product specific allocation. The energy and electricity factors describe the relation between the product specific energy/electricity input and the average energy/electricity input to the refinery

Product	Relative energy use	Electricity factor
Bitumen and coke	0.7	1.11
Heavy fuel oil	0.7	0.90
Light fuel oil	1	0.70
Diesel	1	0.70
Kerosene	1.0	0.60
Petrol	1.8	1.59
Naphtha	0.6	1.59
Propane/ Butane	1.5	1.41
Fuel Gas	1.5	0.95
Sulphur	1.5	1.00

Energy and material flows of Swiss and European refineries have been analysed. The analysis leads to product specific allocation factors for energy, catalysts and waterborne pollutants. Furthermore, consumption of working materials, requirement of additives, production wastes, and infrastructure are included in the inventory. Emission factors and energy uses for the two Swiss refineries are based on available information from questionnaires. Average emission factors for the European refinery had to be estimated based on available information for about 10% of the refineries. Energy consumption figures for European refineries are based on the reported range of figures (IPPC 2001). For heat (and partly electricity) production in refineries, specific boilers are considered using refinery gas and residues from the refining processes.

Airborne emissions comprise CO, CO_2, SO_2, NO_X, particulate matter, hydrocarbons (specified), acids and heavy metals (specified). Waterborne pollutants comprise hydrocarbons (specified), and inorganic substances (sulphates, phosphates, nitrate). Different production wastes and their further treatment are distinguished (Doka 2003). In addition to that, land use and water consumption are recorded. Land use of refineries is based on actual figures of Western European refineries and literature data.

4.3.5 Storage and regional distribution

Regional distribution includes intermediate storage of oil products in large tanks and the supply to the customer (households, companies and filling stations). The requirements and emissions during regional distribution are modelled on a product-specific basis. Vapour emission control is modelled according to the today situation where most of the stocks and filling stations are equipped with emission control. Land use figures for regional stocks stem from Swiss statistics. Besides the infrastructure and the energy consumption for the movement of goods, production wastes (sludge from oil sumps and oil tanks), and hydrocarbon emissions (specified) are included on a product-specific basis. Additionally land use, and waterborne pollutants are recorded.

4.3.6 Fuel oil boilers

Three different sizes of boilers are considered, namely 10 kW, 100 kW and 1 MW. The manufacturing of boilers including tank room and chimney is considered. The operation phase includes process- and fuel-specific emissions. Emissions and efficiencies are differentiated according to the fuel used (light and heavy fuel oil) and the technology applied (condensing and non-condensing, Low-NO_x-technology). Hydrocarbons are reported individually, sulphur dioxide and metal emissions are calculated based on the fuel composition listed in Tab. 4.1 assuming no retention technology. For condensing boilers the emission of waterborne pollutants (condensation water) is accounted for. The annual use efficiencies vary between 94% and 100%.

4.3.7 Oil power plants

National average efficiencies of oil power plants are used for 20 different countries (see Tab. 4.5). Co-production of heat in oil power plants is considered as a rise of electric efficiency according to the exergy of the two power plant products heat and electricity. An average chemical composition of the fuel is used for the European countries (see Tab. 4.1). Power plant emissions of CO_2, NO_X, SO_2 and particulate matter rely in most cases on national official sources (administrations or national utilities). For other pollutants (CO, N_2O, trace elements, waterborne pollutants) average figures have been used if specific data were not available. Requirements and waterborne emissions of the cooling circulation are also included in the process data. For the infrastructure of power plants an average land use figure based on literature data is used.

Tab. 4.5 Ratio between energy input and electricity output for oil power plants in Europe

Land	Year	TJ_{In}/TJ_e
Belgium	1992	2.83
Germany	1999	3.47
Denmark	1999	3.47
Finland	2000	1.62
France	1999	2.30
Greece	1999	2.64
Great Britain	1999	3.50
Ireland	1999	2.62
Italy	2000	2.61
Former Yugoslavia	estimation	2.98
Croatia	2001	2.88
The Netherlands	1999	2.26
Austria	2001	2.54
Portugal	2000	2.82
Sweden	2001	1.88
Slovenia	2000	2.50
Slovakia	1999	2.80
Spain	2001	2.95
Czech Republic	1999	3.67
Hungary	1999	2.68

4.3.8 Life cycle inventories

The full life cycle inventories with the unit process raw data for all production stages can be found in the ecoinvent database and in the final report (Jungbluth 2004).

4.4 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

Tab. 4.6 shows selected LCI results and the cumulative energy demand for different stages of oil production with an example for oil power plants (average RER). Results for other types of uses, i.e. for heating or powertrains can be found in the database.

The contributions of different stages are visualized in Fig. 4.2. For some of these stages averages have been calculated which cannot be found as datasets in the database (e.g. average crude oil production for supply to Europe). The demand of fossil energy resources for the crude oil and natural gas is inventoried with the exploration even if the energy content is delivered from stage to stage with the products. Land occupation is dominated by exploration and regional distribution. About 90% of CO_2 Emissions are caused by the combustion of the fuel oil. Also NO_x, SO_x and particles are mainly emitted in this stage. Emissions of NO_x during crude oil production are mainly in low populated areas while combustion in the power plant is assumed to take place in highly populated areas. Methane emissions are caused due to the venting of gas during crude oil production activities. BOD emissions are caused by oil spills and discharges. Cadmium emissions to soil are caused by several background processes.

Tab. 4.6 Selected LCI results and the cumulative energy demand for different stages of the average European oil chain from oil extraction to the use of heavy fuel oil in the power plant

		Name		crude oil, mix, at production	crude oil, mix, at long distance transport	heavy fuel oil, at refinery	heavy fuel oil, at regional storage	heavy fuel oil, burned in power plant
		Location		GLO	RER	RER	RER	RER
		Unit	Unit	kg	kg	kg	kg	kg
LCIA results								
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	48.9	49.6	52.2	52.6	52.8
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.1E-1	5.1E-1	7.1E-1	8.3E-1	8.5E-1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.7E-2	7.7E-2	1.1E-1	1.3E-1	1.3E-1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	7.9E-3	1.3E-2	1.8E-2	2.1E-2	2.2E-2
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	5.1E-3	8.3E-3	1.2E-2	1.5E-2	1.5E-2
LCI results								
resource	Land occupation	total	m2a	4.6E-3	5.5E-3	6.3E-3	7.9E-3	8.3E-3
air	Carbon dioxide, fossil	total	kg	1.6E-1	2.1E-1	3.7E-1	3.9E-1	3.6E+0
air	NMVOC	total	kg	1.1E-3	1.1E-3	1.5E-3	1.5E-3	1.7E-3
air	Nitrogen oxides	high population density	kg	3.8E-5	5.1E-5	2.3E-4	2.4E-4	**8.5E-3**
air	Nitrogen oxides	low population density	kg	**9.2E-4**	**1.1E-3**	**1.2E-3**	**1.3E-3**	1.3E-3
air	Nitrogen oxides	lower stratosphere + upper troposphere	kg	8.3E-13	1.3E-12	4.8E-11	4.8E-11	4.8E-11
air	Nitrogen oxides	unspecified	kg	1.5E-4	2.9E-4	3.1E-4	4.2E-4	4.9E-4
air	Nitrogen oxides	total	kg	1.1E-3	1.5E-3	1.8E-3	1.9E-3	1.0E-2
air	Sulphur dioxide	total	kg	2.4E-3	3.0E-3	3.9E-3	4.0E-3	2.5E-2
air	Particulates, < 2.5 um	total	kg	1.0E-4	1.3E-4	1.7E-4	1.9E-4	5.2E-4
water	BOD	total	kg	1.2E-2	1.4E-2	1.5E-2	1.5E-2	1.5E-2
soil	Cadmium	total	kg	2.1E-11	3.1E-11	4.2E-11	1.2E-10	1.2E-10
Further LCI results								
air	Methane, fossil	total	kg	1.5E-3	1.6E-3	1.8E-3	1.8E-3	2.0E-3
soil	Oils, unspecified	total	kg	4.7E-3	4.7E-3	5.0E-3	5.0E-3	5.0E-3
water	Oils, unspecified	total	kg	3.9E-3	4.4E-3	4.7E-3	4.7E-3	4.8E-3

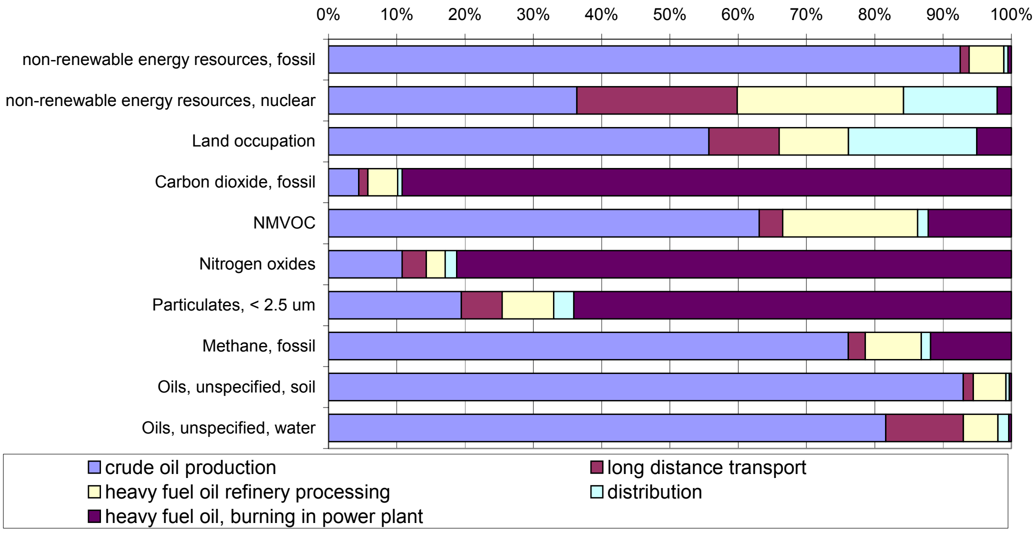

Fig. 4.2 Contribution of different stages to the total emissions of selected pollutants and cumulative energy demands.

Selected LCI results and the cumulative energy demand are compared in Tab. 4.7 for different regions of crude oil production. Higher cumulative fossil energy demands for crude oil from Nigeria and Russia are caused by high amounts of flared or vented natural gas. The comparison shows that for many parameters there might be a high variation between different regions. Thus it is important to consider the actual supply situation for the inventory of crude oil products. The last row of Tab. 4.7 shows the situation considered for the supply of crude oil to Europe.

Tab. 4.7 Selected LCI results and the cumulative energy demand for different regions of crude oil production

		Name		crude oil, at production	crude oil, at production offshore	crude oil, at production offshore	crude oil, at production onshore	crude oil, at production onshore	crude oil, at production offshore	crude oil, at production onshore	crude oil, at production onshore	crude oil, mix, at production
		Location		NG	NO	NL	NL	RME	GB	RU	RAF	GLO
		Unit	Unit	kg	kg	kg	kg	kg	kg	kg	kg	kg
		Infrastructure		0	0	0	0	0	0	0	0	0
LCIA results												
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	53.6	46.8	46.5	46.3	47.3	48.1	53.6	49.9	48.9
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	4.5E-2	1.2E-2	4.4E-2	5.4E-2	5.5E-2	2.7E-2	1.3E+0	4.5E-1	3.1E-1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	7.2E-3	2.1E-3	4.9E-3	5.7E-3	8.4E-3	4.6E-3	2.0E-1	6.8E-2	4.7E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.1E-3	3.0E-4	2.8E-3	3.1E-3	1.4E-3	6.5E-4	3.3E-2	1.2E-2	7.9E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	8.1E-4	2.9E-4	3.2E-3	3.3E-3	9.7E-4	5.7E-4	2.1E-2	7.5E-3	5.1E-3
LCI results												
resource	Land occupation	total	m2a	6.8E-4	8.0E-4	2.5E-3	7.1E-4	8.0E-4	1.5E-3	2.1E-2	1.8E-3	4.6E-3
air	Carbon dioxide, fossil	total	kg	4.2E-1	5.8E-2	4.5E-2	3.0E-2	9.3E-2	1.8E-2	4.4E-1	2.5E-1	1.6E-1
air	NMVOC	total	kg	6.0E-3	1.4E-3	1.2E-4	9.0E-5	4.9E-4	3.7E-5	1.7E-3	1.2E-3	1.1E-3
air	Nitrogen oxides	total	kg	2.0E-3	3.1E-4	3.1E-4	9.3E-5	8.1E-4	2.0E-4	3.1E-3	1.5E-3	1.1E-3
air	Sulphur dioxide	total	kg	3.3E-5	3.9E-5	9.0E-5	2.6E-5	2.0E-4	7.6E-5	1.2E-2	3.7E-4	2.4E-3
air	Particulates, < 2.5 um	total	kg	4.3E-5	2.1E-5	3.3E-5	6.3E-6	8.6E-5	2.4E-5	3.1E-4	1.1E-4	1.0E-4
water	BOD	total	kg	2.8E-4	3.6E-4	1.1E-3	2.5E-5	3.1E-4	2.2E-3	6.4E-2	5.8E-4	1.2E-2
soil	Cadmium	total	kg	5.6E-12	2.3E-12	9.5E-12	6.3E-12	6.4E-12	5.7E-12	8.5E-11	1.7E-11	2.1E-11
Further LCI results												
air	Methane, fossil	total	kg	1.3E-2	2.3E-4	2.8E-4	2.5E-4	8.1E-4	3.6E-5	3.1E-3	2.4E-3	1.5E-3
soil	Oils, unspecified	total	kg	1.0E-5	1.5E-5	2.5E-5	4.8E-6	7.8E-5	4.1E-5	2.5E-2	9.1E-5	4.7E-3
water	Oils, unspecified	total	kg	7.5E-5	4.6E-5	6.7E-5	4.9E-6	8.6E-5	6.9E-4	2.0E-2	1.7E-4	3.9E-3
		Share for refinery in Europe	%	3%	23%	0%	0%	27%	18%	18%	11%	100%

Tab. 4.8 shows selected LCI results and the cumulative energy demand for different petrol products in Switzerland and Europe. The table shows also differences for the delivery at the gate of the refinery or to final consumer. The delivery to the Swiss consumer takes the import of petrol to Switzerland from Europe into account. Low-sulphur petrol is produced with additional efforts for desulphurisation and thus shows some higher results for the elementary flows.

Tab. 4.8 Selected LCI results and the cumulative energy demand for different petrol products in Switzerland and Europe

		Name		petrol, unleaded, at refinery	petrol, unleaded, at refinery	petrol, unleaded, at regional storage	petrol, unleaded, at regional storage	petrol, low-sulphur, at regional storage	petrol, low-sulphur, at regional storage	petrol, two-stroke blend, at regional storage	petrol, two-stroke blend, at regional storage
		Location		CH	RER	CH	RER	CH	RER	CH	RER
		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	55.8	56.2	57.2	56.5	57.5	56.9	57.5	56.9
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	6.9E-1	9.0E-1	1.0E+0	1.0E+0	1.0E+0	1.0E+0	1.0E+0	1.1E+0
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.3E-1	1.3E-1	1.8E-1	1.5E-1	1.8E-1	1.6E-1	1.8E-1	1.6E-1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.3E-2	2.3E-2	2.3E-2	2.6E-2	2.3E-2	2.6E-2	2.4E-2	2.7E-2
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.0E-2	1.5E-2	1.9E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.1E-2
LCI results											
resource	Land occupation	total	m2a	3.2E-3	7.3E-3	1.2E-2	1.0E-2	1.2E-2	1.0E-2	1.2E-2	1.0E-2
air	Carbon dioxide, fossil	total	kg	6.0E-1	6.2E-1	6.9E-1	6.5E-1	7.1E-1	6.7E-1	6.9E-1	6.5E-1
air	NMVOC	total	kg	3.4E-3	1.6E-3	2.7E-3	2.1E-3	2.7E-3	2.1E-3	2.9E-3	2.3E-3
air	Nitrogen oxides	total	kg	2.5E-3	2.2E-3	2.9E-3	2.4E-3	3.0E-3	2.4E-3	2.9E-3	2.4E-3
air	Sulphur dioxide	total	kg	2.1E-3	5.9E-3	5.0E-3	6.1E-3	5.1E-3	6.2E-3	5.0E-3	6.1E-3
air	Particulates, < 2.5 um	total	kg	1.6E-4	2.3E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4	2.5E-4
water	BOD	total	kg	1.8E-3	1.5E-2	1.2E-2	1.6E-2	1.2E-2	1.6E-2	1.2E-2	1.6E-2
soil	Cadmium	total	kg	6.1E-11	6.5E-11	5.0E-10	1.4E-10	5.0E-10	1.4E-10	5.1E-10	1.6E-10

Tab. 4.9 shows selected LCI results and the cumulative energy demand for average heavy fuel oil power plants in some European countries. The magnitude of different elementary flows might be quite different. A basic reason for the above is the different efficiencies of electricity production. However, also air emission levels are shown to be quite different depending on the technologies used for treatment of raw gas. This shows that it is quite important to consider the right inventories for power plants and that it is not sufficient to use average assumptions, e.g. a European power plant in a life cycle inventory for a specific country.

Tab. 4.9 Selected LCI results and the cumulative energy demand for some European heavy fuel oil power plants

		Name		electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant	electricity, oil, at power plant
		Location		DE	DK	FI	GB	IE	SE	CZ	HU	SK	HR	SI
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0	0	0	0
LCIA results														
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	16.03	11.40	7.49	16.16	12.59	8.66	16.93	12.39	12.95	13.72	11.54
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.6E-1	1.8E-1	1.2E-1	2.6E-1	2.0E-1	1.4E-1	2.7E-1	2.0E-1	2.1E-1	2.2E-1	1.9E-1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.9E-2	2.8E-2	1.8E-2	4.0E-2	3.1E-2	2.1E-2	4.2E-2	3.0E-2	3.2E-2	3.4E-2	2.8E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	6.5E-3	4.6E-3	3.1E-3	6.6E-3	5.1E-3	3.5E-3	6.9E-3	5.0E-3	5.3E-3	5.6E-3	4.7E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	4.6E-3	3.2E-3	2.1E-3	4.6E-3	3.6E-3	2.5E-3	4.8E-3	3.5E-3	3.7E-3	3.9E-3	3.3E-3
LCI results														
resource	Land occupation	total	m2a	2.5E-3	1.8E-3	1.2E-3	2.6E-3	2.0E-3	1.4E-3	2.7E-3	2.0E-3	2.0E-3	2.2E-3	1.8E-3
air	Carbon dioxide, fossil	total	kg	1.11	0.80	0.51	1.11	0.84	0.59	1.17	0.84	0.89	0.93	0.80
air	NMVOC	total	kg	5.0E-4	3.5E-4	2.4E-4	5.2E-4	4.1E-4	2.6E-4	5.5E-4	3.9E-4	4.2E-4	4.5E-4	3.7E-4
air	Nitrogen oxides	total	kg	1.3E-3	2.6E-3	1.0E-3	4.1E-3	2.2E-3	1.3E-3	3.5E-3	1.9E-3	4.7E-3	2.1E-3	1.1E-3
air	Sulphur dioxide	total	kg	3.0E-3	9.1E-3	3.1E-3	1.2E-2	1.4E-2	1.8E-3	4.8E-3	1.1E-2	4.6E-3	1.1E-2	1.1E-3
air	Particulates, < 2.5 um	total	kg	1.4E-4	1.1E-4	1.1E-4	1.4E-4	1.2E-4	8.6E-5	1.7E-4	2.7E-4	1.2E-3	2.3E-4	1.1E-4
water	BOD	total	kg	4.6E-3	3.3E-3	2.2E-3	4.7E-3	3.6E-3	2.5E-3	4.9E-3	3.6E-3	3.9E-3	4.0E-3	3.3E-3
soil	Cadmium	total	kg	3.7E-11	2.6E-11	1.7E-11	3.7E-11	2.9E-11	2.0E-11	3.9E-11	2.9E-11	3.0E-11	3.2E-11	2.7E-11

4.5 Conclusions and outlook

The modelling for crude oil exploration to the different uses of oil products considers all important stages of the process chain. The inventories consider the situation in Europe and Switzerland for the year 2000. As far as possible and necessary specific inventories for single countries have been investigated. These inventories can be regarded as representative for these stages. User of the database can make use of the inventories for all relevant stages as background data and for comparisons.

Main shortcomings exist for the modelling of crude oil exploration in the Middle East. Only very little information was available. If possible, the specific situation should be investigated into more details in future. The refinery model is very complex. It has to be based on pieces of information from different sources and thus it might not give a fully representative picture. Thus the model might not be able to address the specific situation in one single out of the 100 operating European refineries. There might be quite relevant differences between different refineries or average supply situations for different countries that might be addressed in a future update. Such an update should also address new fuel specification, e.g. for sulphur-free fuels. However, the model developed here provides a suitable picture for representing the average burdens from a European refinery into cumulative results for the oil chain.

Emission factors for power plants show a high variation. Not all air emissions could be investigated for the same reference year. A comparison of the updated life cycle inventory with older inventories shows that a large technological development and the establishment of lower air emission standards have occurred in the last years. The actual situation must be followed up for future updates.

4.6 References

BP Amoco 2001	BP Amoco (2001) BP Amoco statistical review of world energy june 2001. BP Amoco, London, retrieved from: www.bp.com/centres/energy/.
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, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
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. 1996	Frischknecht R., Bollens U., Bosshart S., Ciot M., Ciseri L., Doka G., Dones R., Gantner U., Hischier R. and Martin A. (1996) Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut, Villigen, Bundesamt für Energie (Hrsg.), Bern, CH, retrieved from: www.energieforschung.ch.
IPPC 2001	IPPC (2001) Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques for Mineral Oil and Gas Refineries. European Commission Directorate-general JRC, Joint Research Centre, Seville, Spain, retrieved from: http://eippcb.jrc.es.
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.

5 Natural Gas

Authors: Mireille Faist Emmenegger, ESU-services; Thomas Heck, PSI; Niels Jungbluth, ESU-services

5.1 Introduction

The system model “Natural Gas” describes the production, distribution and combustion of natural gas for industrial and domestic applications in Switzerland and Western Europe. The inventory datasets for natural gas include gas field exploration, natural gas production, natural gas purification, long distance transport, regional distribution and combustion in boilers and power plants. The inventories for all these steps account for energy and material requirements, production wastes, and the production of the infrastructure as well as air- and waterborne pollutants. Transport services needed to supply the processes with energy and materials are included, as well as waste treatment processes.

In order to represent current electricity production in Europe, average installed natural gas and industrial gas power plants have been considered. Additionally, a dataset for the most advanced combined cycle technology currently available at the market has been included. For natural gas heating systems, boilers with advanced technology available at the market around the year 2000 have been modelled.

For the first time, quantitative estimates of uncertainties for all input data are included. The uncertainty factors, provided in the database as well, are the basis for the calculation of uncertainties of the cumulative results. In this short report, the uncertainties of the input data are not discussed.

Here, only a short overview is provided. For further details, the reader may refer to the full report (Faist Emmenegger et al. 2004).

5.2 Chemical and physical properties

The composition and physical properties of natural gas from different regions are listed in Tab. 5.1 and for coke oven gas and blast furnace gas in Tab. 5.2.

Tab. 5.1: Chemical composition, heating values and density of natural gas produced in different countries, of average natural gas delivered in Europe and Switzerland (Aróstegui 1997, DGMK 1992, SWISSGAS 1999, ExternE 1999).

	Unit	Norway	The Nether-lands	Germany	Russian Federa-tion	Algeria	Great Britain	Europe	Switzer-land
		Nm^3	Nm^3	Nm^3	Nm^3	Nm^3	Nm^3	Nm^3	Nm^3
Main elements:									
Methane	kg	0.719	0.671	0.690	0.716	0.654	0.667	0.700	0.678
Ethane	kg	0.074	0.023	0.008	0.006	0.100	0.041	0.026	0.033
Propane	kg	0.019	0.003	0.001	0.002	0.016		0.006	0.013
Butane	kg	0.006	0.001		0.001	0.003		0.002	0.006
C5+	kg	0.002			0.001		0.035	0.001	0.003
NMVOC	kg						0.006		
CO_2	kg	0.013	0.008	0.002	0.001		0.036	0.006	0.011
CO	kg						0.667		
Nitrogen	kg	0.007	0.118	0.062	0.007	0.006	0.041	0.061	0.020
Trace elements:									
Sulphur	mg	2	2	2	2	2	2	2	1.63/ 8.41)
Mercury	µg	10	10	10	10	10	2	1	0
Heating values:									
H_l [1])	MJ	44.9	38.4	38.5	40.0	42.3	40.7	40.4	40.2
H_u [2])	MJ	40.8	34.9	35.0	36.4	38.5	37.0	36.8	36.5
Density	kg/l	0.84	0.82	0.76	0.73	0.78	0.78	0.80	0.76

[1]): after odorization

[2]): H_l: lower heating value (net calorific value)

[3]): H_u: upper heating value (gross calorific value)

Tab. 5.2: Chemical composition and heating values of blast furnace and coke oven gas Cerbe *et al.* 1999.

	CH_4 Vol-%	H_2 Vol-%	CO Vol-%	CO_2 Vol-%	N_2 Vol-%	Rest Vol-%	H_l [1)] MJ/m^3	H_u [2)] MJ/m^3
blast furnace		4.1	21.4	22.0	52.5		3.3	3.2-4[3)]
coke oven gas	25.3	54.5	5.5	2.3	9.6	2.8	17.6[4)]	19.8

[1]): H_l: lower heating value (net calorific value)

[2]): H_u: upper heating value (gross calorific value)

[3)] (IPIS 2003)

[4)] (DVFG 2003)

5.3 System description

The natural gas upstream chain is modeled with the following process steps: natural gas production (which includes exploration, production at field, purification), long-distance transportation, regional distribution, and local supply (Fig. 5.1).

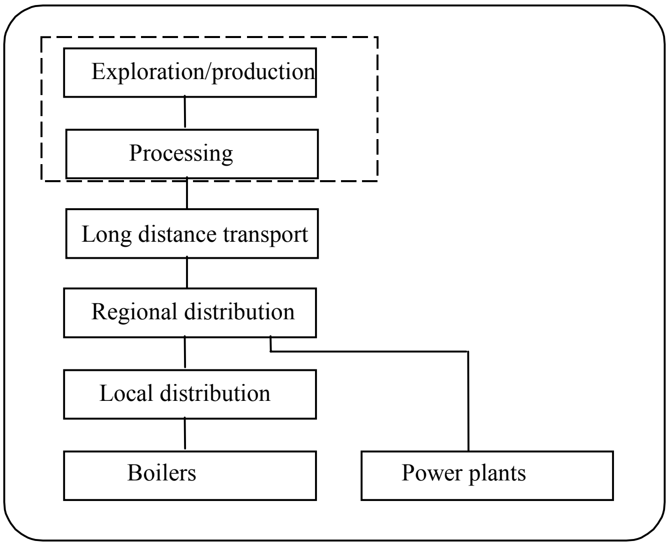

Fig. 5.1 Overview of the modelling for the gas production chain

Tab. 5.3 shows key factors for the natural gas supply and for the average natural gas power plants in the investigated countries and regions. The main producer countries for the supply of natural gas in Western European and Switzerland are the Russian Federation, The Netherlands, Norway, Germany, Great Britain and Algeria. Their shares of the supply in different countries are described in Tab. 5.3. Natural gas sold in a country is assumed to be a mix of its domestic production and imports. Exports are treated like domestic sales. The import structure is decisive for the gas transport distances and for the environmental burdens related to the upstream chain.

Tab. 5.3 Key parameters of analyzed natural gas supply in different countries and regions (VSG 2001, BP Amoco 2001).

	AT	BE	CH	DE	ES	FR	IT	NL	UCTE	CENTR-EL	NORD-EL	GB
Natural gas supply:												
From Germany	5%	2%	10%	18%					5%	4%		
From The Netherlands		50%	28%	19%		14%	8%	83%	24%			
From Russian Federation	86%		36%	36%		31%	28%		34%	80%	43%	
From Norway	8%	46%	17%	21%	27%	28%		8%	17%	3%		
From Algeria/North Africa			4%		73%	26%	41%		16%	1%		
From Danmark				3%							6%	
From Great Britain		2%	5%	3%		2%		9%	4%			
Own production minus exports							23%			12%	51%	100%
Lower heating value (MJ/Nm^3)	34.8	37.1	36.5	35.0	39.1	38.0	38.1	34.9	36.8	34.6	36.7	37.0

5.3.1 Natural gas exploration

Because drilling is the same for oil and gas, the same emission and production factors per meter drilled borehole are used (Jungbluth 2003). Drilling is included in the data sets “natural gas, at production, (country)”. Demand varies between 1.8 m and 7.0 m per Mio. m^3 natural gas extracted (MEZ 2000; OLF 2001; WEG 2001). Geophysical prospection is excluded due to negligible contributions to total emissions and resource requirements.

5.3.2 Natural gas production

The requirements and emissions of natural gas production per cubic meter natural gas extracted is modelled for the following regions:

- North Sea (NL, NO, GB)
- Onshore Germany
- Algeria, Russian Federation, Nigeria.

If necessary (and possible) a regional distinction is made between onshore and offshore production. Data are mostly based on environmental reports of companies operating in the modelled areas; on the basis of these data it was not possible to differentiate between production and purification in the Netherlands and in Germany. Data for onshore and offshore production in the Netherlands were aggregated in the environmental report. The inventory was calculated separately for on- and offshore production on the basis of the energy content of the produced natural gas. Disposal of waste is mainly based on data from the North Sea (Norwegian production). Few specific data were available for Algeria and Russian Federation. For these countries, average data were used. In the system model, thermal and off-grid electric energy required in natural gas production is provided by natural gas motors and turbines. The allocation for the combined oil and gas production is based on the lower heating value (net calorific value) of crude oil and natural gas. Methane leakages in the production of natural gas vary between 0.07 g/Nm^3 (Norway) and 3.1 g/Nm^3 (Russian Federation) (Nisbet 2001; OLF 2001), thermal energy used in production between 0.17 MJ/Nm^3 and 0.5 MJ/Nm^3 (OLF 2001; Faist Emmenegger et al. 2004). Production processes of certain chemicals used in natural gas exploration could not be analysed and are therefore not included in the inventory tables. Although partly emitted to the sea, these chemicals are neither considered as specific waterborne pollutants.

5.3.3 Natural gas purification

Natural gas is treated to eliminate water and oil, higher hydrocarbons, and sulphur. Sweet gas and sour gas are considered separately. Sour gas has an elevated content of sulphur and CO_2. In particular the content of H_2S is about 6 vol.-% for sour gas. In the sweetening process sulphur is eliminated from the sour gas to 99.9%.

5.3.4 Long distance transportation

Energy requirements for compressor stations and gas leakages are considered as well as construction of pipelines and requirements for control flights along the pipelines. The compressors are driven by gas turbines fed with a share of the gas transported. A substantial share of Algerian natural gas is shipped as liquefied natural gas (LNG). Energy requirements and emissions of this transport way are included in separate data sets. Compression and regasification as well as ship transport are included. Methane leakage rate is assumed 1.4% for the total average distance (6’000 km) for the transmission of natural gas from the Russian Federation and about 0.026% per 1000 km pipeline for the other producer countries. For the LNG tanker transport from Algeria to Italy the leakage rate is 0.04% (Snam 1999). Energy use in the compressor stations of the pipelines is estimated at 1.8% of transported gas per 1’000 km in Europe and of 2.7% per 1’000 km for the Russian Federation (personal communications with industrial experts). Energy use of the LNG freight ship is about 0.01 Nm^3 per tkm (Snam 1999; 2000).

5.3.5 Regional distribution and local supply

The process of regional distribution and local supply includes the construction of the gas pipelines usually operated with an over pressure of 0.1 to 1 bar. The infrastructure data sets include excavation of ditches, production of steel, cast iron and polyethylene tubes, polyethylene and bitumen for the cover, and sand and cement for embedding the tubes. Control trips with private cars and helicopters are included as well. Gas leakages (0.02% on the high pressure level, additional 0.72% on the low pressure level for the Swiss supply situation) (Liechti 2002; Reichert & Schön 2000; Seifert 1998) and land use during construction and operation are considered.

5.3.6 Natural gas boilers

Tab. 5.4 shows the names of the datasets available in the ecoinvent database for heat at different natural gas boilers. The technology refers to boilers available at the market in Switzerland around year 2000 except for the low-NO_x models which refer to the mid 1990s.

Emissions and efficiencies are differentiated according to the technology applied (e.g. modulating and non-modulating, condensing and non-condensing). The relatively new modulating gas boilers are now well established at the market in Switzerland. In a modulating boiler, the firing rate is flexibly adjusted to the heat demand. A condensing boiler uses additionally the latent heat in the steam of the flue gas in order to increase the efficiency. Modern modulating condensing natural gas boilers can reach efficiencies of 102% over the year (Aebischer *et al.* 2002). The efficiency refers to the lower heating value (net calorific value), this is why values over 100% are possible. Non-condensing modulating boilers have efficiencies of about 96%.

For modelling it has been assumed that the small boilers (<100 kW) are connected to the low pressure distribution network and that the large boilers (>100 kW) are connected to the high pressure network. For the high pressure network, average European conditions have been considered. The low pressure distribution network has been modelled for Switzerland only; therefore Swiss low pressure natural gas has been used as approximation of average European low pressure supply. This implies that the Swiss natural gas mix has been used as an approximation of the European natural gas mix for the small boilers. Tab. 5.3 shows that this is an acceptable assumption because the shares of the producer countries in the natural gas supply mix of Switzerland and average UCTE are similar. In particular, the high share of Russian natural gas is almost the same for Switzerland as it is for average UCTE.

Tab. 5.4 Ecoinvent dataset for heat at modern natural gas boilers located in Europe.

Name	Unit
heat, natural gas, at boiler modulating <100kW	MJ
heat, natural gas, at boiler modulating >100kW	MJ
heat, natural gas, at boiler condensing modulating <100kW	MJ
heat, natural gas, at boiler condensing modulating >100kW	MJ
heat, natural gas, at boiler atmospheric non-modulating <100kW	MJ
heat, natural gas, at boiler fan burner non-modulating <100kW	MJ
heat, natural gas, at industrial furnace >100kW	MJ
heat, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW *	MJ
heat, natural gas, at boiler atmospheric low-NOx non-modulating <100kW *	MJ
heat, natural gas, at boiler fan burner low-NOx non-modulating <100kW *	MJ
heat, natural gas, at industrial furnace low-NOx >100kW *	MJ

* low-NOx refers to old low-NOx technology available in about mid 1990s

Extensive measurement data of NO_x and CO emissions from modern boilers in Switzerland have been available (SVGW 2002). The NO_x and CO measurements have been performed under controlled conditions; no adjustment to real operation was made due to lack of information. Other emission factors have been derived from different references. For condensing boilers the emission of waterborne pollutants (water of condensation) is accounted for.

Fig. 5.2 illustrates the relative frequency distribution of NO_x emissions during operation of modern modulating condensing boilers as an example. The data are based on about 400 measurements (SVGW 2002). The variation is represented by an uncertainty factor in the database given as the square of the geometric standard deviation of the lognormal approximation. An uncertainty analysis based on a lot of measurements as shown in Fig. 5.2 could be performed only for NO_x and CO emissions of natural gas boilers. In most cases, uncertainties were either estimated from ranges of different values available in literature or derived from basic uncertainty estimates and pedigree factors as described in the ecoinvent methodology (Frischknecht et al. 2004).

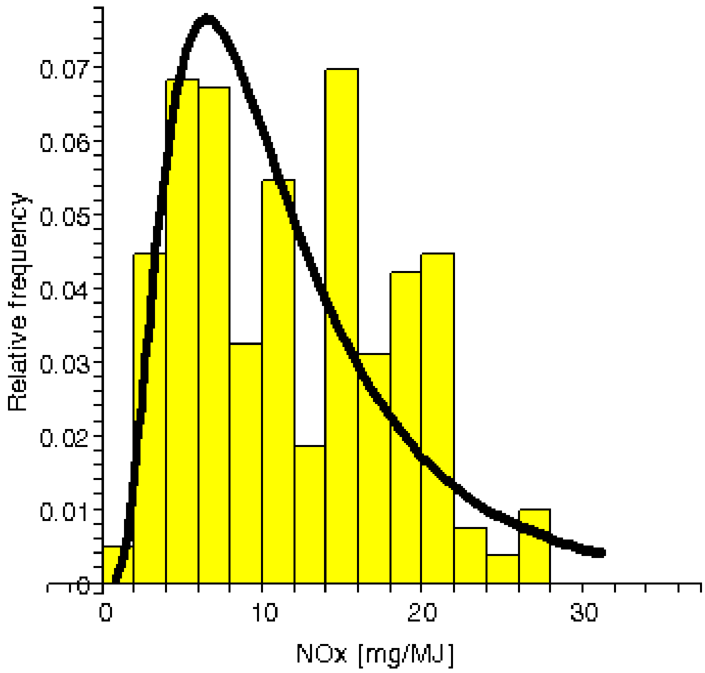

Fig. 5.2 Normalised distribution of NO_x emissions from modulating condensing natural gas boilers < 100 kW, derived from measurements in (SVGW 2002). Solid line: Lognormal approximation.

5.3.7 Natural gas and industrial gas power plants

In this study, natural gas power plants and industrial gas power plants are treated separately. Tab. 5.5 shows the datasets for electricity production at natural gas power plants available in the ecoinvent database. The datasets "electricity, natural gas, at power plant" refer to average natural gas power plants operating around year 2000 in the specified country or region. For the modelling of the infrastructure, a capacity of about 100 MW_e has been assumed. For electricity production at a standard gas turbine of about 10 MW_e, only a dataset describing generic worldwide conditions is provided. The modelled combined cycle power plant has a power rate of about 400 MW_e (265 MW_e from the gas turbine and 135 MW_e from the steam engine). It is assumed to be located in Europe.

The fuel used in the natural gas power plants is directly supplied by high pressure gas pipelines. For the modelling of average natural gas power plants in different countries and different regions, national average efficiencies of gas power plants are used. Tab. 5.6 shows the calculated average efficiencies for different UCTE countries and the UCTE average. Heat production in combined heat and power (CHP) operation lowers the electric efficiency of the power plant. In order to consider heat supply, the national average efficiency was corrected by an exergy factor for heat (Faist Emmenegger et al. 2004). If no large CHP power plants were considered, the electric net electric efficiency of UCTE natural gas power plants would be about 40%. If CHP is included, the uncorrected net electric efficiency (total net electricity production divided by total fuel burned) decreases to 36% and thus one would penalise CHP production. The exergy-corrected net electric efficiency lies in between (at 38%, see Tab. 5.6). The exergy-corrected efficiency has been used for countries for which appropriate data were available. For the calculation of net electricity production from reported gross electricity production with and without CHP, losses of 7% due to self-consumption (IEA 2001) have been considered. Besides the

UCTE countries with significant natural gas power production (AT, BE, DE, ES, FR, IT, LU, NL), Great Britain as well as the regions CENTREL and NORDEL have been modelled. Switzerland has currently no large natural gas power plant. Nevertheless, the use of natural gas in small cogeneration units is quite common in Switzerland. Small heat and power cogeneration plants are treated in a separate chapter in ecoinvent (Heck 2004).

Tab. 5.5 Ecoinvent dataset for electricity production at natural gas power plants.

Name	Unit	Country/Region *)
electricity, natural gas, at power plant	kWh	AT
electricity, natural gas, at power plant	kWh	BE
electricity, natural gas, at power plant	kWh	DE
electricity, natural gas, at power plant	kWh	ES
electricity, natural gas, at power plant	kWh	FR
electricity, natural gas, at power plant	kWh	GB
electricity, natural gas, at power plant	kWh	IT
electricity, natural gas, at power plant	kWh	LU
electricity, natural gas, at power plant	kWh	NL
electricity, natural gas, at power plant	kWh	CENTREL
electricity, natural gas, at power plant	kWh	NORDEL
electricity, natural gas, at power plant	kWh	UCTE
electricity, natural gas, at turbine, 10MW	kWh	GLO
electricity, natural gas, at combined cycle plant, best technology	kWh	RER

*) Country codes see (Frischknecht et al. 2004)

Tab. 5.6 Natural gas input, electricity production, and calculated efficiencies of natural gas power plants in UCTE countries; CHP (combined heat and power) is considered. Data for year 1999, source: (IEA 2001). n/a: not available.

		AT	BE	DE	ES	FR	IT	LU*)	NL	UCTE
Natural Gas Input without CHP	TJ	11169	137029	421440	27664	49805	475109	804	n/a	
Electricity Production, Gross	GWh	1360	16376	55063	2643	7530	49482	59	n/a	
Electricity Production, Net	GWh	1265	15230	51209	2458	7003	46018	55	n/a	
CHP Natural Gas Input	TJ	81717	27078	148055	110183	n/a	301682	n/a	491520	
CHP El. Production, Gross	GWh	7348	2855	n/a	16415	n/a	37501	n/a	49303	
CHP El. Production, Net	GWh	6834	2655	n/a	15266	n/a	34876	n/a	45852	
CHP Heat Production	TJ	16679	16393	126587	2205	n/a	n/a	980	79397	
El. Efficiency without CHP		0.41	0.40	0.44	0.32	0.51	0.35	0.25		0.40
El. Efficiency incl. CHP		0.31	0.39		0.46		0.37		0.34	0.36
Exergy Corrected El. Efficiency incl. CHP		0.35	0.41		0.47				0.37	0.38
Efficiency used in this study		**0.35**	**0.41**	**0.44**	**0.47**	**0.51**	**0.37**	**0.25**	**0.37**	**0.38**

*) for LU: UCTE gas assumed; 1997 power generation data (IEA 2001)

For the natural gas combined cycle power plant, the best current technology has been assumed. Data from the new 400 MW_e power plant Mainz-Wiesbaden (Germany) were used for the modelling of the combined-cycle plant. According to the operators, this is (as of year 2001) the natural gas power plant with the highest net electric efficiency (58.4%) worldwide (KMW 2002). Because the efficiency depends also on the local environmental temperature conditions, the global maximal efficiency is not representative for all locations. It was assumed that a comparable plant at an average location in

Europe would have a net electric efficiency of about 57.5%. In reality, the efficiency depends also on the mode of operation (peak load management, combined heat and power supply). Different modes of operation have not been considered, i.e. optimal electricity production was assumed.

Besides natural gas power plants, industrial gas power plants are described in separate datasets. Industrial gas includes coke oven gas and blast furnace gas. Coke oven gas is a by-product of coke making, whose production is described in the coal chapter (Röder *et al.* 2004). Blast furnace gas is a by-product of the steel production. Tab. 5.7 shows the names of the datasets available in the database for electricity generation at industrial gas power plants. The modelling of electricity from industrial gas power plants is illustrated in Fig. 5.3. Emissions during operation of coke oven gas plants and blast furnace gas plants are considered. The electricity mix is modelled according to national electricity production statistics. Materials of infrastructure are extrapolated form natural gas power plants. The burdens from coking are allocated to the products according to their heating value. Therefore, the production of coke oven gas is partly allocated to the electricity from industrial gas. By contrast, the burdens from the steel production are all allocated to the produced pig iron, none to the produced blast furnace gas.

Tab. 5.7 Ecoinvent dataset for electricity production at industrial gas power plants.

Name	Unit	Country/Region
electricity, industrial gas, at power plant	kWh	AT
electricity, industrial gas, at power plant	kWh	BE
electricity, industrial gas, at power plant	kWh	DE
electricity, industrial gas, at power plant	kWh	ES
electricity, industrial gas, at power plant	kWh	FR
electricity, industrial gas, at power plant	kWh	IT
electricity, industrial gas, at power plant	kWh	NL
electricity, industrial gas, at power plant	kWh	CENTREL
electricity, industrial gas, at power plant	kWh	NORDEL
electricity, industrial gas, at power plant	kWh	UCTE

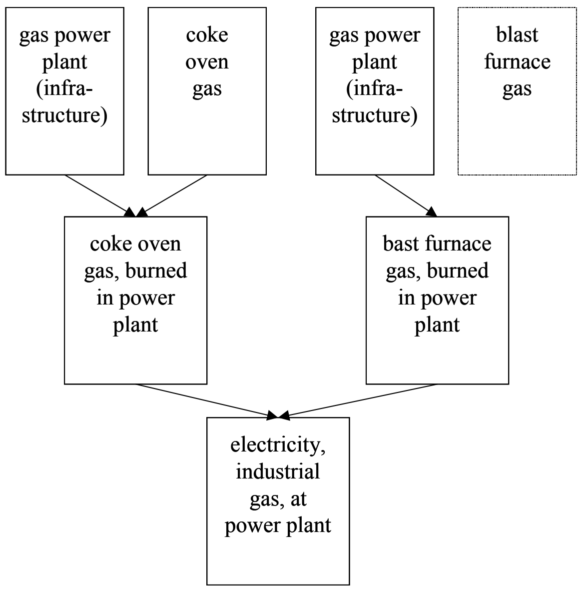

Fig. 5.3 Structure of the major datasets for industrial gas power plants. Blast furnace gas (dashed box) is treated as by-product of steel production; i.e. the production of blast furnace gas is completely allocated to steel production and therefore it is not considered in the electricity production chain.

5.4 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

5.4.1 Selected results

Tab. 5.8 shows selected LCI results and the cumulative energy demand for different stages of natural gas supply.

Tab. 5.8 Selected LCI results and cumulative energy demand for different stages of natural gas supply

		Name		natural gas, mix for CH, at production	natural gas, at long-distance pipeline	natural gas, high pressure, at consumer	natural gas, low pressure, at consumer
		Location		GLO	CH	CH	CH
		Unit	Unit	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.13	1.22	1.24	1.26
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	9.2E-4	1.5E-3	2.3E-3	2.7E-3
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.4E-3	1.7E-3	2.0E-3	2.1E-3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	4.0E-5	5.5E-5	6.4E-5	7.3E-5
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	4.5E-5	5.9E-5	7.3E-5	1.2E-4
LCI results							
resource	Land occupation	total	m2a	2.2E-5	2.9E-5	3.9E-5	6.4E-5
resource	Land transformation	from artificial surface	m2	1.4E-7	2.0E-7	2.7E-7	3.6E-7
resource	Land transformation	to artificial surfaces	m2	1.3E-5	1.4E-5	1.4E-5	1.5E-5
air	Carbon dioxide, fossil	total	kg	2.0E-3	6.2E-3	7.4E-3	7.6E-3
air	NMVOC	total	kg	2.0E-5	2.5E-5	2.7E-5	3.8E-5
air	Nitrogen oxides	high population density	kg	1.2E-7	**1.3E-5**	**1.6E-5**	**1.7E-5**
air	Nitrogen oxides	low population density	kg	**5.6E-6**	6.3E-6	6.5E-6	6.7E-6
air	Nitrogen oxides	lower stratosphere + upper troposphere	kg	3.4E-15	4.7E-15	5.7E-15	3.5E-14
air	Nitrogen oxides	unspecified	kg	6.5E-7	2.9E-6	4.1E-6	4.6E-6
air	Nitrogen oxides	total	kg	6.4E-6	2.2E-5	2.7E-5	2.8E-5
air	Sulphur dioxide	total	kg	2.3E-5	2.7E-5	2.7E-5	2.8E-5
air	Particulates, < 2.5 um	total	kg	4.7E-7	8.0E-7	9.7E-7	1.1E-6
water	BOD	total	kg	4.5E-6	5.7E-6	6.5E-6	7.4E-6
soil	Cadmium	total	kg	1.8E-13	3.4E-13	4.5E-13	7.6E-13
Further LCI results							
air	Methane, fossil	high population density	kg	1.5E-8	3.9E-7	4.8E-7	5.7E-7
air	Methane, fossil	low population density	kg	**3.6E-5**	**1.5E-4**	**1.6E-4**	**3.0E-4**
air	Methane, fossil	lower stratosphere + upper troposphere	kg	1.2E-17	1.7E-17	2.0E-17	1.2E-16
air	Methane, fossil	unspecified	kg	3.4E-9	1.2E-8	2.6E-8	2.9E-8
air	Methane, fossil	total	kg	3.6E-5	1.5E-4	1.6E-4	3.0E-4

The following tables show selected LCI results and cumulative energy demands for application of natural gas for electricity production in power plants and for heat production in boilers.

Tab. 5.9 Selected LCI results and cumulative energy demands for electricity generation at UCTE natural gas power plants.

		Name		electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant	electricity, natural gas, at power plant
		Location		AT	BE	DE	ES	FR	IT	LU	NL	UCTE
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0	0
LCIA results												
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	14.6	10.0	10.6	9.2	8.6	11.6	18.1	11.8	11.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.02	0.01	0.02	0.03	0.02	0.03	0.04	0.01	0.02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.7E-2	8.4E-3	1.6E-2	2.4E-2	1.8E-2	2.4E-2	3.2E-2	4.6E-3	2.1E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	6.6E-4	4.4E-4	6.7E-4	9.7E-4	5.2E-4	9.2E-4	1.1E-3	7.5E-4	7.2E-4
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	8.6E-4	6.1E-4	6.5E-4	7.8E-4	6.6E-4	8.3E-4	1.2E-3	9.4E-4	7.8E-4
LCI results												
resource	Land occupation	total	m2a	5.0E-4	3.5E-4	3.9E-4	4.3E-4	4.1E-4	4.6E-4	6.8E-4	4.2E-4	4.4E-4
air	Carbon dioxide, fossil	total	kg	7.1E-1	5.2E-1	5.2E-1	5.0E-1	4.6E-1	6.2E-1	9.3E-1	5.8E-1	6.0E-1
air	NMVOC	total	kg	5.5E-4	1.0E-4	3.1E-4	1.4E-4	1.9E-4	3.6E-4	4.2E-4	9.2E-5	2.7E-4
air	Nitrogen oxides	total	kg	8.1E-4	5.5E-4	5.3E-4	5.7E-4	5.6E-4	8.5E-4	1.1E-3	6.0E-4	7.2E-4
air	Sulphur dioxide	total	kg	5.4E-4	3.3E-5	3.0E-4	3.2E-5	1.3E-4	3.2E-4	3.4E-4	2.0E-5	2.2E-4
air	Particulates, < 2.5 um	total	kg	2.0E-5	1.1E-5	1.1E-5	1.3E-5	1.2E-5	1.5E-5	2.2E-5	1.2E-5	1.4E-5
water	BOD	total	kg	5.8E-5	2.8E-5	3.5E-5	3.5E-5	3.4E-5	3.8E-5	8.8E-5	3.0E-5	5.7E-5
soil	Cadmium	total	kg	7.1E-12	2.7E-12	4.3E-12	4.0E-12	4.4E-12	4.7E-12	7.0E-12	3.4E-12	4.5E-12
Additional LCI results												
air	Methane	total	kg	3.7E-3	2.3E-4	1.4E-3	5.0E-4	1.1E-3	1.4E-3	2.3E-3	2.4E-4	1.5E-3

Tab. 5.10 Selected LCI results and cumulative energy demands for electricity generation at combined cycle natural gas power plant, best technology.

		Name		electricity, natural gas, at combined cycle plant, best technology
		Location		RER
		Unit	Unit	kWh
		Infrastructure		0
LCIA results				
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	7.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.4E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	5.1E-4
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	5.6E-4
LCI results				
resource	Land occupation	total	m2a	2.9E-4
air	Carbon dioxide, fossil	total	kg	4.0E-1
air	NMVOC	total	kg	1.8E-4
air	Nitrogen oxides	total	kg	3.3E-4
air	Sulphur dioxide	total	kg	1.5E-4
air	Particulates, < 2.5 um	total	kg	1.1E-5
water	BOD	total	kg	4.0E-5
soil	Cadmium	total	kg	3.2E-12
Additional LCI results				
air	Methane	total	kg	9.9E-4

Tab. 5.11 Selected LCI results and cumulative energy demands for electricity generation at industrial gas power plants.

		Name		electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant	electricity, industrial gas, at power plant
		Location		AT	BE	DE	ES	FR	IT	NL	UCTE
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	15.3	4.2	6.3	4.9	1.4	1.4	0.0	3.7
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.37	0.10	0.15	0.12	0.03	0.03	0.00	0.09
	cumulative energy demand	renewable energy resources,	MJ-Eq	5.8E-2	1.6E-2	2.4E-2	1.9E-2	5.4E-3	5.5E-3	2.5E-4	1.4E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	9.2E-3	2.5E-3	3.8E-3	3.0E-3	8.3E-4	8.4E-4	9.6E-6	2.2E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	8.1E-2	2.3E-2	3.3E-2	2.6E-2	7.3E-3	7.4E-3	3.7E-5	2.0E-2
LCI results											
resource	Land occupation	total	m2a	4.5E-2	1.2E-2	1.8E-2	1.4E-2	4.0E-3	4.1E-3	6.2E-5	1.1E-2
air	Carbon dioxide, fossil	total	kg	7.3E-1	1.7E+0	1.4E+0	1.4E+0	2.0E+0	2.0E+0	2.0E+0	1.7E+0
air	NMVOC	total	kg	5.0E-3	1.4E-3	2.1E-3	1.6E-3	4.9E-4	5.0E-4	5.2E-5	1.2E-3
air	Nitrogen oxides	total	kg	2.3E-3	1.2E-3	1.3E-3	1.1E-3	8.9E-4	8.9E-4	7.1E-4	1.1E-3
air	Sulphur dioxide	total	kg	2.2E-3	7.6E-4	1.0E-3	8.2E-4	3.9E-4	3.9E-4	2.0E-4	6.9E-4
air	Particulates, < 2.5 um	total	kg	1.1E-3	3.0E-4	4.4E-4	3.4E-4	1.0E-4	1.1E-4	1.1E-5	2.6E-4
water	BOD	total	kg	1.6E-4	4.4E-5	6.5E-5	5.1E-5	1.5E-5	1.5E-5	1.0E-6	3.9E-5
soil	Cadmium	total	kg	2.1E-11	5.9E-12	8.8E-12	6.9E-12	2.0E-12	2.0E-12	6.8E-14	5.2E-12
Further LCI results											
air	Methane	total	kg	5.3E-3	1.5E-3	2.2E-3	1.7E-3	4.9E-4	4.9E-4	1.0E-5	1.3E-3

Tab. 5.12 Selected LCI results and cumulative energy demands for heat at modern natural gas boilers (available at Swiss market around year 2000).

		Name		heat, natural gas, at boiler condensing modulating <100kW	heat, natural gas, at boiler condensing modulating >100kW	heat, natural gas, at boiler modulating <100kW	heat, natural gas, at boiler modulating >100kW	heat, natural gas, at boiler atmospheric non-modulating <100kW	heat, natural gas, at boiler fan burner non-modulating <100kW	heat, natural gas, at industrial furnace >100kW
		Location		RER	RER	RER	RER	RER	RER	RER
		Unit	Unit	MJ	MJ	MJ	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0	0	0	0
LCIA results										
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.3	1.2	1.3	1.3	1.4	1.4	1.3
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.02	0.01	0.02	0.01	0.01	0.02	0.01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.5E-3	3.0E-3	4.7E-3	3.2E-3	4.1E-3	4.8E-3	3.2E-3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	4.6E-4	2.2E-4	4.9E-4	2.4E-4	3.7E-4	4.9E-4	2.4E-4
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	4.0E-4	1.7E-4	4.2E-4	1.8E-4	3.5E-4	4.3E-4	1.9E-4
LCI results										
resource	Land occupation	total	m2a	1.1E-4	5.3E-5	1.2E-4	5.7E-5	1.1E-4	1.2E-4	5.7E-5
air	Carbon dioxide, fossil	total	kg	6.4E-2	6.3E-2	6.8E-2	6.7E-2	6.9E-2	6.9E-2	6.7E-2
air	NMVOC	total	kg	4.0E-5	2.6E-5	4.3E-5	2.8E-5	4.5E-5	4.4E-5	2.8E-5
air	Nitrogen oxides	total	kg	4.0E-5	3.9E-5	4.7E-5	4.4E-5	4.8E-5	5.1E-5	4.7E-5
air	Sulphur dioxide	total	kg	3.4E-5	2.5E-5	3.7E-5	2.6E-5	3.5E-5	3.7E-5	2.7E-5
air	Particulates, < 2.5 um	total	kg	1.8E-6	1.2E-6	1.9E-6	1.3E-6	1.8E-6	1.9E-6	1.4E-6
water	BOD	total	kg	9.2E-6	6.3E-6	9.7E-6	6.7E-6	9.6E-6	9.9E-6	6.7E-6
soil	Cadmium	total	kg	1.4E-12	6.3E-13	1.5E-12	6.6E-13	1.4E-12	1.5E-12	6.7E-13
Additional LCI results										
air	Methane	total	kg	3.0E-4	1.6E-4	3.1E-4	1.7E-4	3.2E-4	3.2E-4	1.7E-4

5.4.2 Analysis

Fig. 5.4 shows a graphical analysis of the share of different production stages of the gas supplied to the consumer at the Swiss low pressure network. A major part of the selected flows arises during the production (exploration, field production and purification) of natural gas. Energy requirements are mostly due to production and long-distance transport; distribution uses partly the pressure built up during the long-distance transport. Methane leakages are mainly caused during the transport from the Russian Federation and in the low pressure distribution network. Carbon dioxide is emitted from all stages of the upstream chain, mainly in the long distance transportation and in the exploration/field production. Sulphur dioxide emissions are mainly caused during the gas desulphurisation.

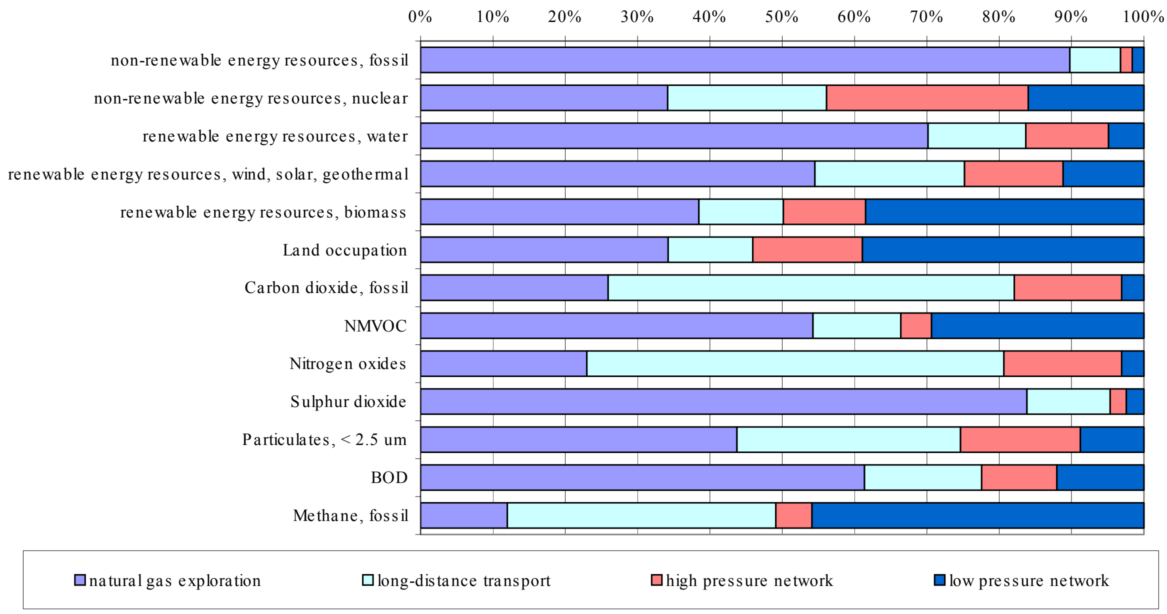

Fig. 5.4 Contribution of different stages to the total emissions of selected pollutants and the cumulative energy demands due to the supply of low pressure natural gas to the consumer in Switzerland.

Fig. 5.5 shows the relative contributions of different stages to the cumulative emissions of a modern natural gas combined cycle power plant located in Europe. The fuel supply mix is the average UCTE natural gas mix at the high pressure network. The figure illustrates that the different cumulative emissions per kWh electricity are distributed very differently over the chain. Carbon dioxide emissions are mainly the direct emissions during the operation of the power plant. Gas transport contributes about 8%, gas production about 3% to total CO_2 emissions. The carbon dioxide emissions due to the infrastructure of the gas power plant are almost negligible in the chain. For carbon monoxide emissions, the emissions during production and transport are dominating. The direct emissions during power plant operation of a modern combined cycle power plant are relatively low. Cumulative methane emissions of a gas power plant at UCTE gas mix originate almost completely from the upstream part of the chain. In particular the natural gas losses due to leakages in the long distance transport from Russian Federation to UCTE area are significant for the total methane emissions. About half of the nitrogen oxide emissions are direct emissions from combined cycle power plant operation.

Whereas the relative distributions of carbon dioxide and methane emissions are more or less representative for gas power plants supplied by average UCTE natural gas, the direct carbon monoxide and nitrogen oxide emissions during operation can vary strongly depending on technology and mode of operation. CO emissions from the considered modern combined cycle power plant occur mainly during part-load operation while CO emissions are much lower at full power.

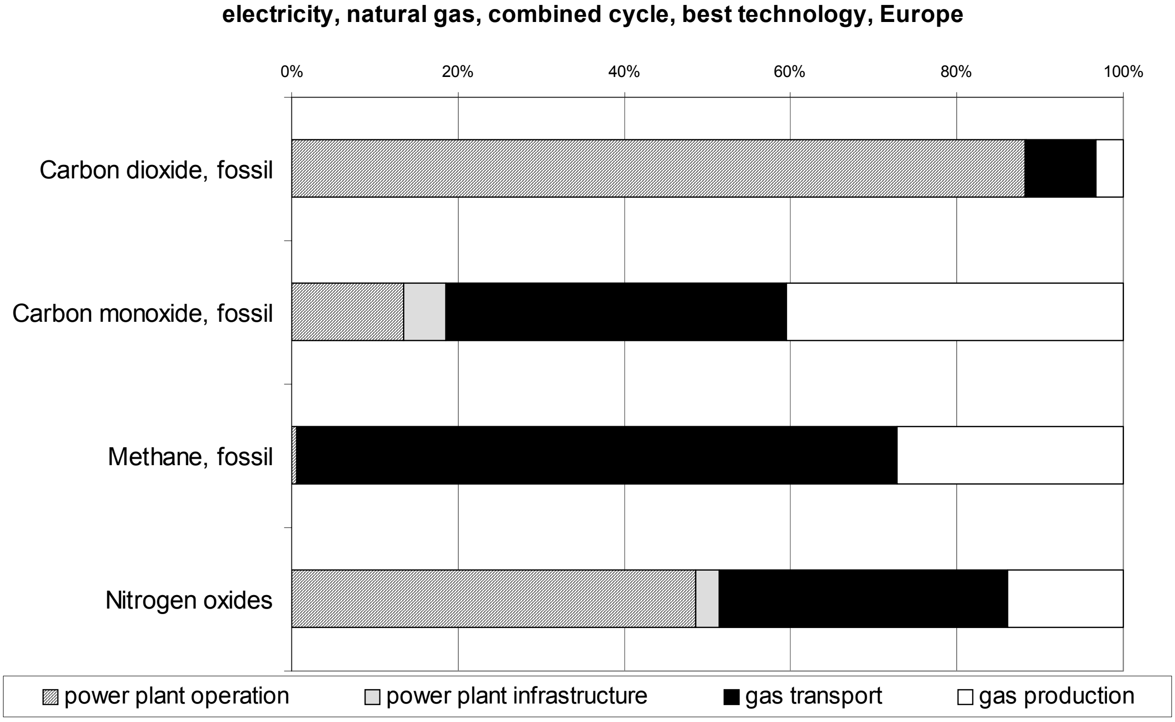

Fig. 5.5 **Contribution of different stages to the cumulative emissions of a natural gas combined cycle power plant, best current technology, at an average location in Europe.**

Fig. 5.6 shows cumulative carbon dioxide emissions of electricity generation at natural gas power plants for different countries. Because the emissions are dominated by direct emissions from power plant operation, the differences in cumulative emissions are essentially determined by the differences of efficiencies. Nevertheless it should be kept in mind that data for CHP have not been available for all countries (cf. Tab. 5.6). Furthermore, „despite the major efforts made by the EU Statistical Office (Eurostat) to achieve a common way of collecting cogeneration statistics, member states still collect them in a different way, and therefore the statistics are not directly comparable" (EDUCOGEN 2001). Consequently, the efficiency calculation is not fully consistent, which is a limitation for comparability of country-specific results. The differences in gas transport distances show up as well, but in total the contribution is of secondary importance for CO_2 emissions. The cumulative methane emissions (Fig. 5.7) are strongly determined by gas transport as well as by the efficiencies. Therefore the variation of the cumulative methane emissions from country to country is very large.

Fig. 5.8 shows the contributions of single processes to the cumulative methane emissions of an average natural gas power plant in Europe. Fig. 5.8 allows some conclusions on the location of the emissions in the chain. The cumulative methane emissions are dominated by emissions during transport from Russian Federation to Western Europe and emissions in Russian Federation during natural gas production.

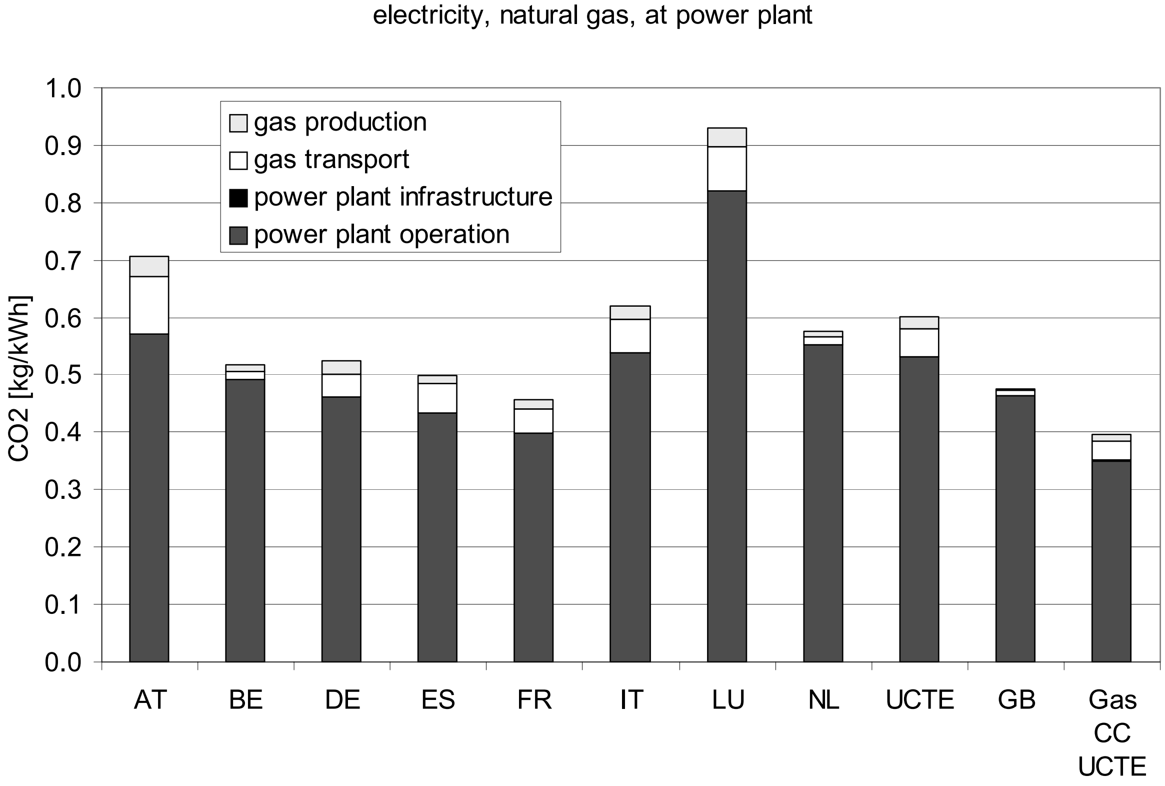

Fig. 5.6 Cumulative CO_2 emissions of electricity production at selected natural gas power plants.

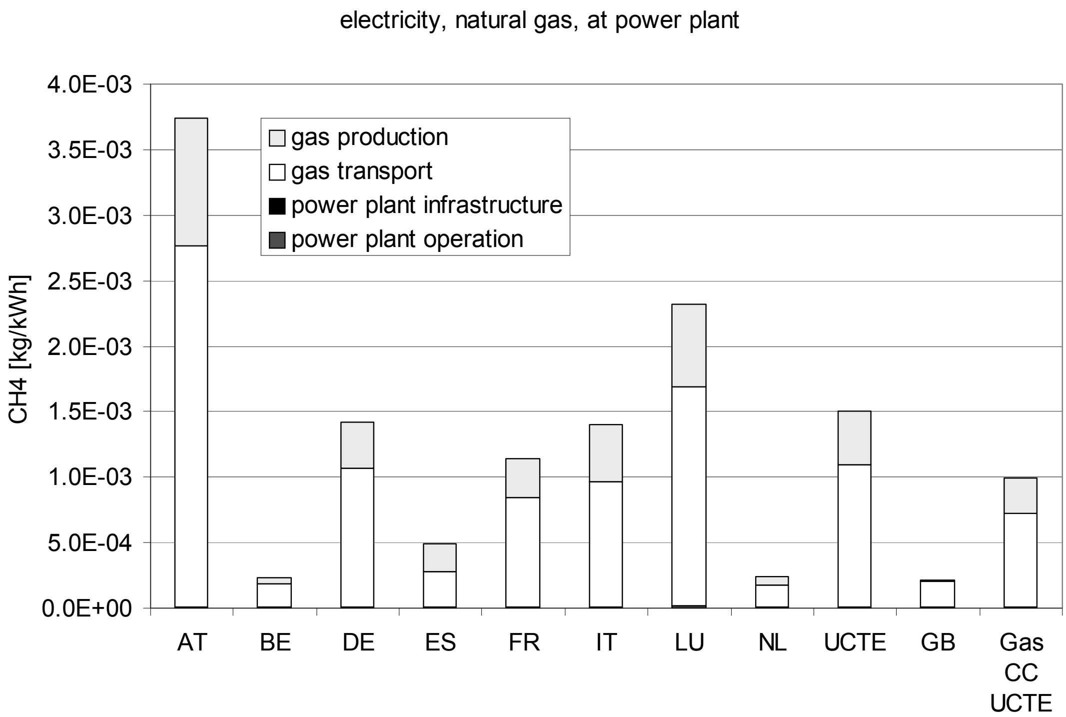

Fig. 5.7 Cumulative CH_4 emissions of electricity production at selected natural gas power plants.

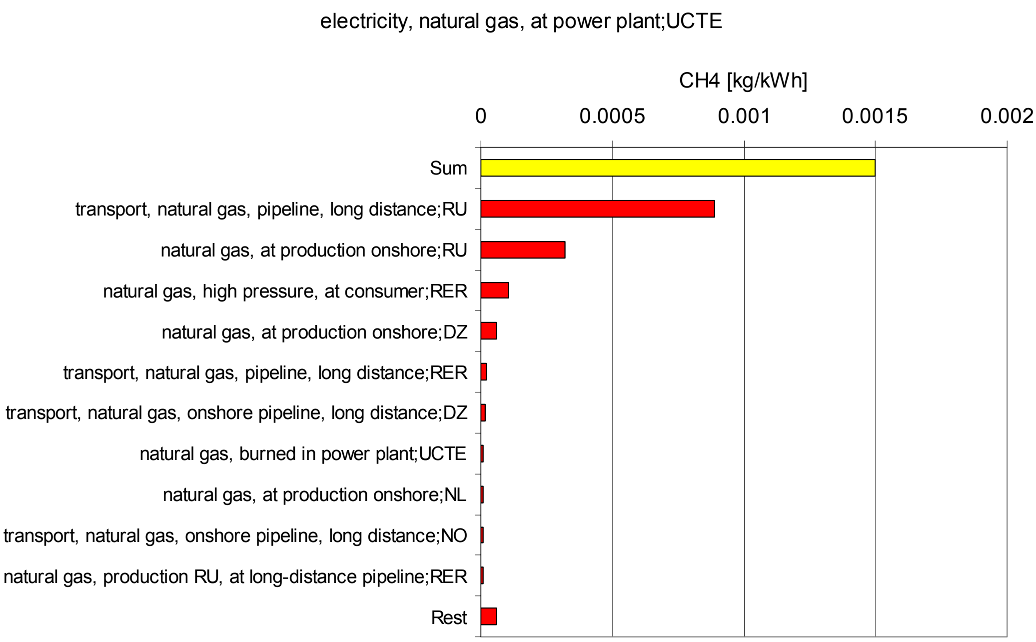

Fig. 5.8 Contributions of single ecoinvent processes to cumulative methane emissions of electricity generation at an average natural gas power plant in Europe. The upper (yellow) bar shows the cumulative total emissions; a red bar represents the cumulative contribution of a single process within the whole chain.

Fig. 5.9 shows cumulative NO_x emissions of electricity generation at natural gas power plants for different countries and, for comparison, the corresponding emissions of a modern combined cycle power plant. Because of the low emissions reported from operation of the combined cycle power plant and because of the high efficiency, the cumulative NO_x emissions for the best technology combined cycle plant are significantly lower than for an average UCTE natural gas power plant.

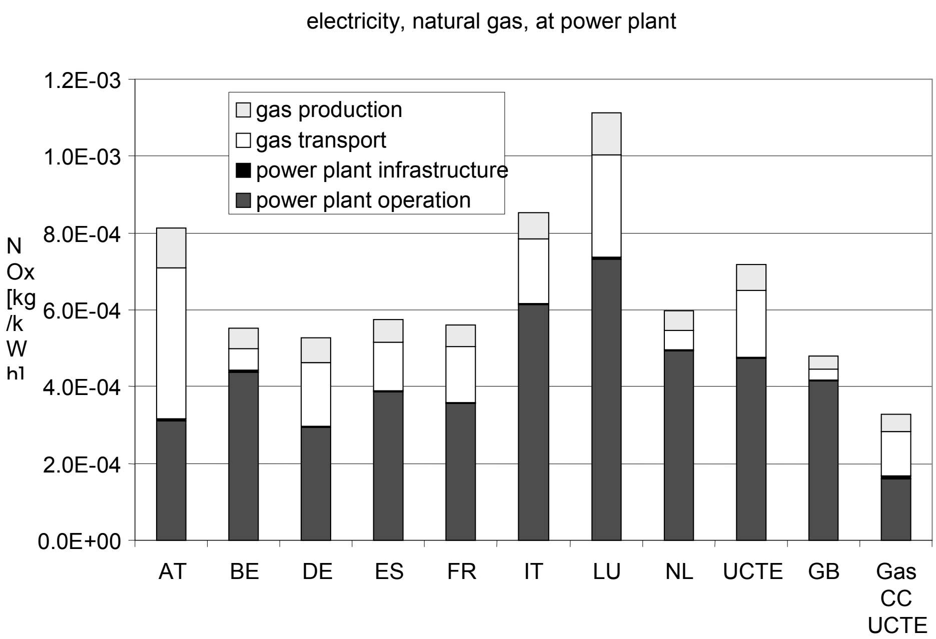

Fig. 5.9 Cumulative NO_x emissions of electricity production at selected natural gas power plants.

Cumulative SO_2 emissions of electricity at natural gas power plants are strongly dominated by emissions from gas production (Fig. 5.10). Therefore, the results differ significantly depending on the origin of the natural gas. Burning of sour gas in the production chain is a major contributor to cumulative SO_2 emissions. Therefore countries with a high share of sour gas in the gas supply chain have relatively high cumulative SO_2 emissions.

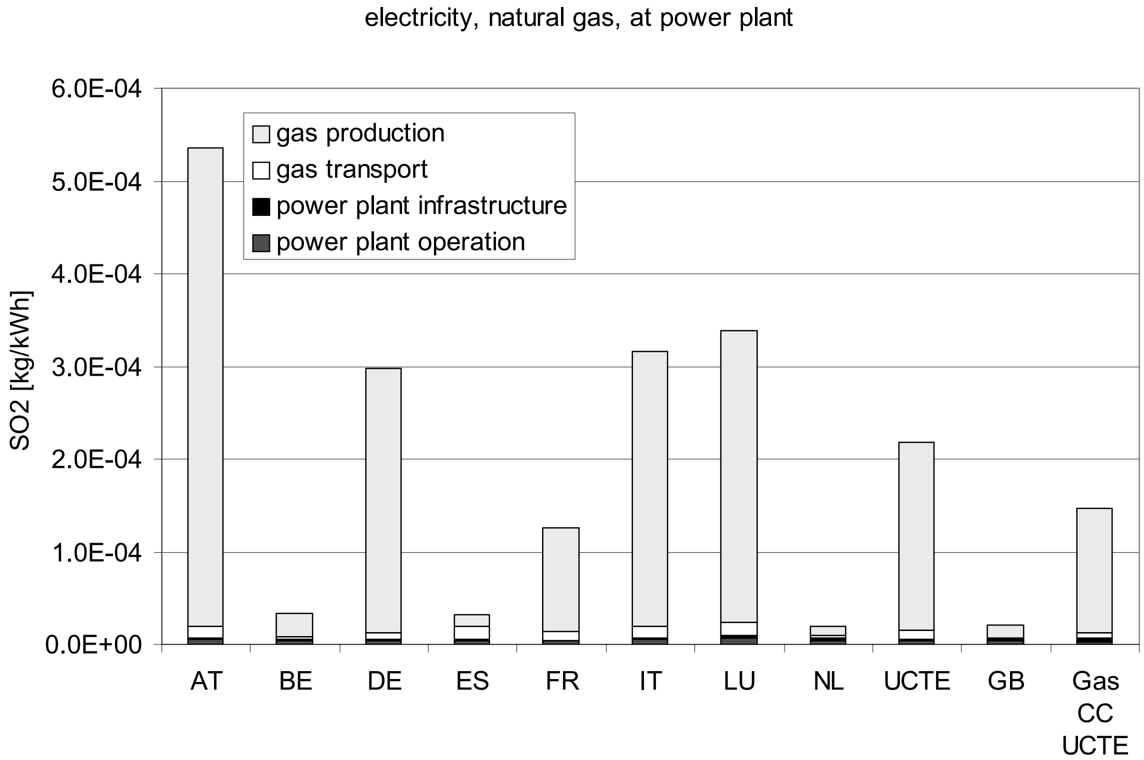

Fig. 5.10 Cumulative SO_2 emissions of electricity production at selected natural gas power plants.

Fig. 5.11 shows cumulative air emissions of arsenic related to electricity generation in natural gas power plants. The cumulative arsenic air emissions are dominated by the power plant infrastructure and the materials used in gas production and transport. Fig. 5.12 shows that the cumulative arsenic air emissions of the combined cycle power plant in Europe are mainly stemming from copper production in region Latin America (RLA). The results indicate that in this point the combined cycle power plant performs worse than an average plant. But because the differences are small and because of the uncertainties of material use in the chain, no final conclusions can be drawn. Such examples show that a further investigation of uncertainties is useful in order to make comparisons more solid.

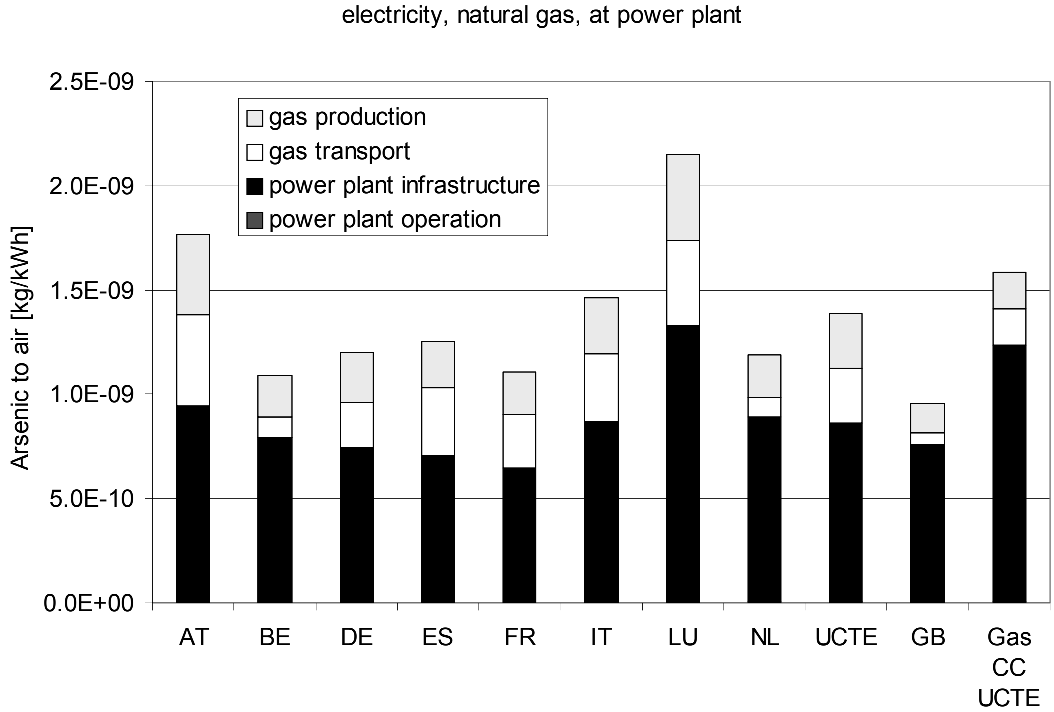

Fig. 5.11 Cumulative arsenic emissions to air of electricity production at selected natural gas power plants.

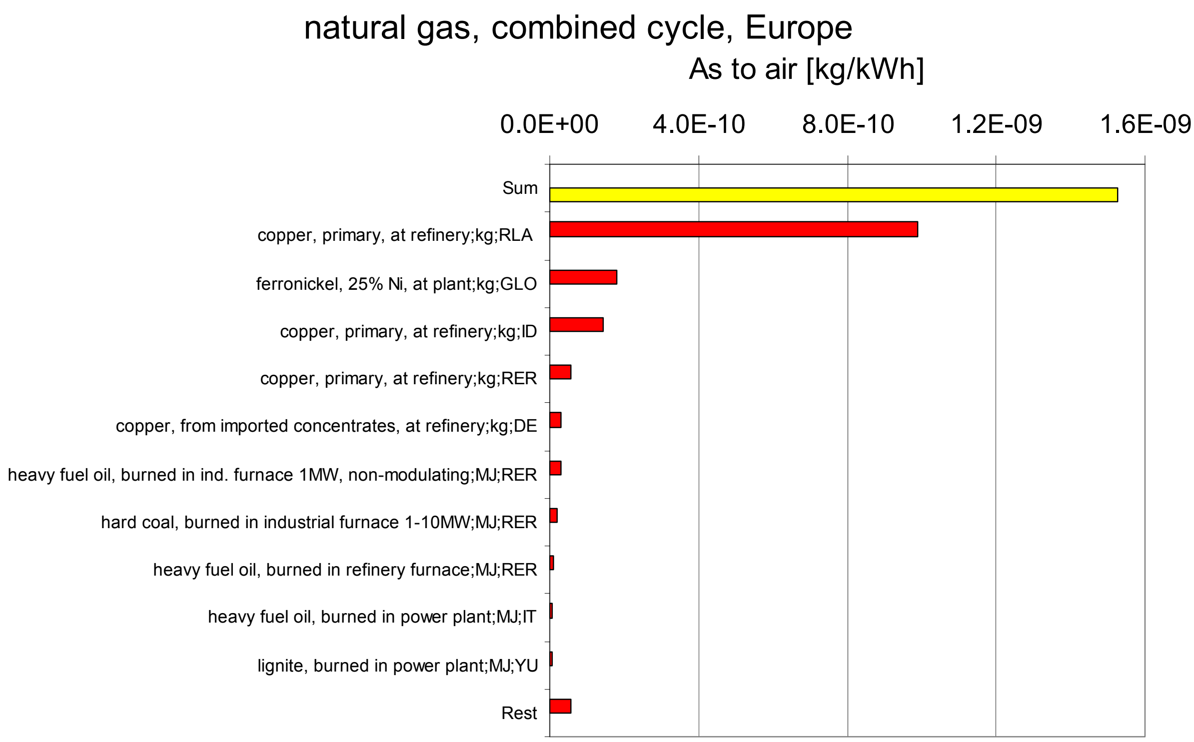

Fig. 5.12 Contributions of single ecoinvent processes to cumulative arsenic air emissions of electricity generation at a modern combined cycle natural gas power plant in Europe. The upper (yellow) bar shows the cumulative total emissions; a red bar represents the cumulative contribution of a single process within the whole chain.

Fig. 5.13 shows an example for the resource uses due to materials for gas power plants in different countries and for the combined gas power plant. Uncertainties of infrastructure data are large; therefore the comparison of results should be viewed with care.

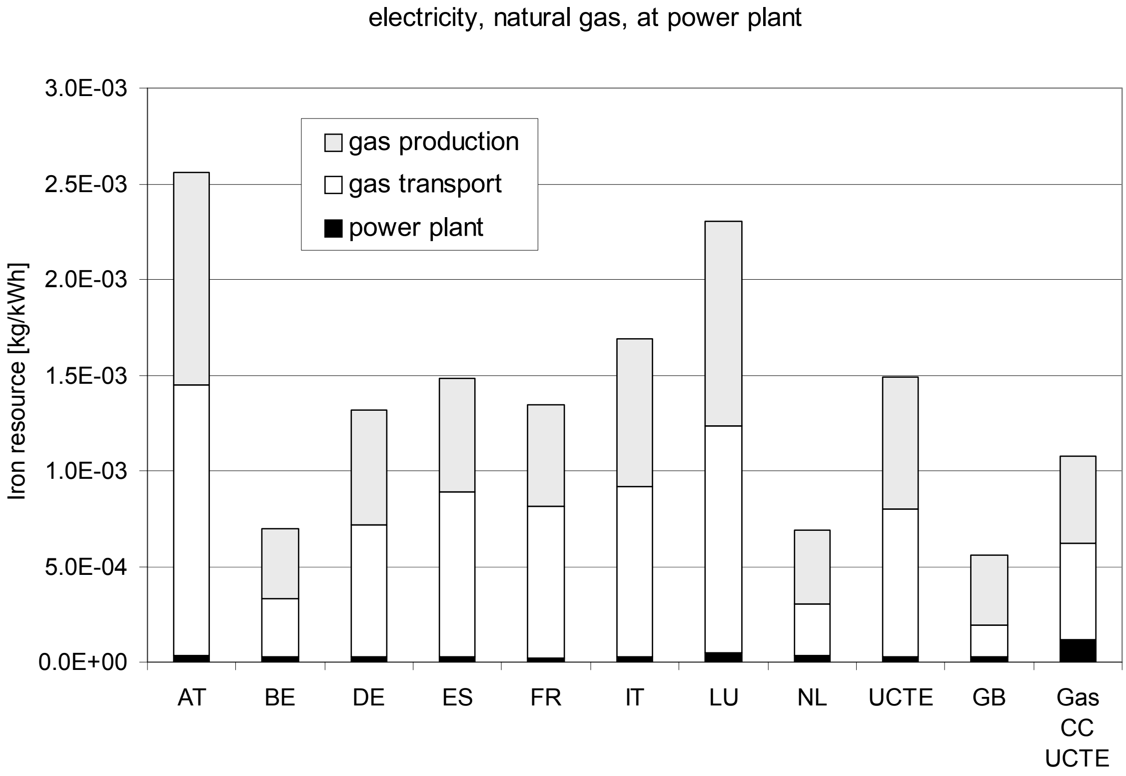

Fig. 5.13 Cumulative use of iron resources in ground of electricity production at selected natural gas power plants

5.5 Conclusions and outlook

An important share of the resulting environmental burdens is generated by the production and processing of natural gas. Emissions per kWh electricity are distributed very differently over the chain for different species (e.g. CO_2, NO_x, CH_4). Carbon dioxide emissions are mainly the direct emissions during the operation of the power plant. For carbon monoxide emissions, the emissions during production and transport are dominating. The direct emissions during power plant operation of a modern combined cycle power plant are relatively low. Cumulative methane emissions of a gas power plant originate almost completely from the upstream part of the chain. In particular the natural gas losses due to leakages in the long distance transport from Russia to UCTE countries are significant for the cumulative methane emissions. The distribution in the low pressure network contributes significantly to cumulative methane emissions. About half of the nitrogen oxide emissions are direct emissions from combined cycle power plant operation for average UCTE gas supply.

The modelling considers all important stages of the process chain from natural gas exploration to the different uses of gas products. The inventories consider the situation in Europe and Switzerland for the year 2000. As far as possible and necessary, specific inventories for single countries have been investigated. These inventories can be regarded as representative for these stages. Users of the database can make use of the inventories for all relevant stages.

Uncertainty still exists for gas leakages during gas production and long distance transportation in the Russian Federation due to incomplete information. There are only few data on the production and transport of natural gas in Algeria. Future assessment should address these steps in more detail.

The combustion of natural gas causes comparatively high emissions of polycyclic hydrocarbons and formaldehydes, but the data sources used for these emission factors are rather old. The content of radionuclides and mercury in natural gas as well as the fate of these substances is uncertain. The particular disposal route of water extracted together with natural gas during gas production is not well known.

Land use for exploration of gas fields is equal to exploration of oil fields (per meter drilled). Land use for gas production and purification is based on literature data and additional assumption concerning the ecosystem quality. Land use of pipelines (long distance transportation and regional distribution) is based on Swiss experiences and assumptions for an extrapolation to natural gas exporting countries. Land use of boilers is disregarded. Land use of power plants is based on literature data and assumptions concerning the yearly electricity production.

Among the considered natural gas boilers available at the market around the year 2000, the modern condensing and modulating boilers have the lowest cumulative CO_2 emissions due to the high possible efficiencies. The modern gas boilers have also relatively low NO_x and CO emissions compared to old boilers. Nevertheless, the analysis of the distributions showed that the measured emission values vary over a broad range, in particular for CO. Large boilers tend to show lower cumulative emissions per MJ than small ones; nevertheless it should be noted that this depends on the location of the boiler at the gas distribution network. In particular the modelled cumulative methane emissions are higher for small than for large boilers. This is essentially an artefact of the modelling and might reflect reality not very well. The reason is the loss in the low pressure distribution network. For the small boilers an average location at the low distribution network was assumed. By contrast, it was assumed that the large boilers are operating near to the high pressure network with negligible losses in between. In individual cases, the cumulative emissions will vary also depending on the location in a country i.e. depending on the individual location at the gas network.

The country averages of the cumulative CO_2 emissions of natural gas power plants in Europe range from 460 to 930 g/kWh$_e$. Total greenhouse gas emissions (i.e. including CO_2, CH_4, N_2O and other greenhouse gases in the chain) range from about 485 to about 990 g CO_2-equiv./kWh$_e$ (for 100 year time horizon after (IPCC 2001)). The differences are essentially determined by the country-specific average efficiencies which depend on different technologies (share of steam power plants, gas turbines, combined cycle plants) and mode of operation (share of peak load, combined heat and power). The average cumulative emissions in UCTE are about 600 g CO_2/kWh$_e$ and about 640 g CO_2-equiv./kWh$_e$. Due to the high efficiency, the modelled combined power plant shows much lower cumulative GHG emissions (about 400 g CO_2/kWh$_e$ and about 423 g CO_2-equiv./kWh$_e$) than the UCTE average. CO_2 emissions due to gas transport play a secondary role but are not negligible for the European average due to the high share of gas transported over long distances.

The situation is different for cumulative methane emissions. These emissions depend strongly on the losses during transport i.e. on the origin of the natural gas in the country. Consequently, the cumulative methane emissions differ between the different countries by more than an order of magnitude. The relatively high cumulative methane of an average UCTE natural gas power plant (1.5 g/kWh$_e$) originate essentially from the high share of Russian natural gas in the mix associated with long distance transport. By contrast, the cumulative methane emissions of an average natural gas power plant in Netherlands are almost one order of magnitude lower than the emissions of the UCTE average because of the high self-production of natural gas in the country. Methane emissions from power plant operation are almost negligible in all cases considered.

SO_2 emissions as well differ significantly depending on the origin of the natural gas because direct emissions of SO_2 from the power plant operation are very low due to the low sulphur content of natural gas supplied to the consumer. In relative terms the major contribution to cumulative SO_2 emissions originate from sour gas burning in the production chain.

5.6 References

Aebischer et al. 2002 — Aebischer B., Catenazzi G., Jakob M., Jochem E., Kumbaroglu G., Madlener R., Dones R., Gantner U., Hirschberg S., Kypreos S., Lienin S., Röder A., Frischknecht R., Jungbluth N., Faist M. and Schwarz J. (2002) CO2-Reduktionspotential Erdgas. Projekt-phase 1: Referenzsze-nario., Zürich.

Aróstegui 1997 — Aróstegui M. (1997) ExternE National Implementation Spain, Final Re-port. CIEMAT.

BP Amoco 2001 — BP Amoco (2001) BP Amoco statistical review of world energy June 2001. BP Amoco, London, retrieved from: www.bp.com/centres/energy/.

Cerbe et al. 1999 — Cerbe G., Carlowitz O., Kätelhön J. E., Köhler H., Lehmann J., Lendt B., Lethen H., Mauruschat H. and Pietsch H. (1999) Grundlagen der Gas-technik: Gasbeschaffung, Gasverteilung, Gasverwendung. 5., vollständig neubearbeitete Auflage Edition. Carl Hanser Verlag, ISBN 3-446-21109-8, München Wien.

DGMK 1992 — DGMK (1992) Ansatzpunkte und Potentiale zur Minderung des Treib-hauseffektes aus Sicht der fossilen Energieträger, Forschungsbericht 448-2. Deutsche Wiss. Gesellschaft für Erdöl, Erdgas und Kohle e.V., Ham-burg.

DVFG 2003 — DVFG (2003) Flüssiggas Internet Information. Deutscher Verband für Flüssiggas (DVFG), Berlin, Germany, retrieved from: http://www.dvfg.de/frames/flue/h.htm.

EDUCOGEN 2001 — EDUCOGEN (2001) EDUCOGEN. Second Edition, December 2001. COGEN Europe, Brussels, Belgium, retrieved from: http://www.cogen.org/projects/educogen.htm.

ExternE 1999 — ExternE (1999) UK national implementation study, Table 1: Definition of the gas fuel cycle. Retrieved 10.9.2002 retrieved from: http://externe.jrc.es/7a99file1.htm.

Faist Emmenegger et al. 2004 — Faist Emmenegger M., Heck T. and Jungbluth N. (2004) 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.). Final report ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.

Frischknecht et al. 2004 — Frischknecht R., Althaus H.-J., Doka G., Dones R., Hischier R., Hellweg S., Jungbluth N., Kellenberger D., Nemecek T., Rebitzer G. and Spiel-mann M. (2004) Overview and Methodology. Final report ecoinvent 2000 No. 1. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, re-trieved from: www.ecoinvent.ch.

Heck 2004 — Heck T. (2004) Wärme-Kraft-Kopplung. In: Sachbilanzen von Energie-systemen: Grundlagen für den ökologischen Vergleich von Energiesys-temen 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, Dübendorf, CH retrieved from: www.ecoinvent.ch.

IEA 2001 — IEA (2001) Electricity Information (2001 Edition). International Energy Agency, OECD, Paris.

IPCC 2001 — IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmen-tal Panel on Climate Change. (ed. Houghton J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A.). Cambridge University Press, Cambridge, United Kingdom and New York, USA.

IPIS 2003	IPIS (2003) Roheisen Internet Information. International Pig Iron Secre-tariat (IPIS), Ratingen, Deutschland, retrieved from: http://www.roheisen.de.
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 Vil-ligen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
KMW 2002	KMW (2002) Bericht über das Geschäftsjahr 2001. Kraftwerke Mainz Wiesbaden Aktiengesellschaft, Mainz, Germany, retrieved from: http://www.kmw-ag.de/download/kmw_gb2001.pdf.
Liechti 2002	Liechti A. (2002) Swiss Greenhouse Gas Inventory 2000. Bundesamt für Umwelt, Wald und Landschaft, Bern, CH.
MEZ 2000	MEZ (2000) Oil and gas in the Netherlands: exploration and production 1999. A review of oil and gas exploration and production activities in the Netherlands and the Netherlands sector of the Continental Shelf. Minis-terie van Economische Zaken (Ministry of Economic Affairs), 's-Gravenhage.
Nisbet 2001	Nisbet E. G. (2001) Russian Emissions of Atmospheric Methane: Study of Sources. INTAS 97-2055, 1998-2001. INTAS.
OLF 2001	OLF (2001) Emissions and discharges from the Norwegian Petroleum Industry 2000; prepared for OLF by Novatech a.s. Norwegian Oil Indus-try Association, Stavanger, retrieved from: www.olf.no, www.novatech.no.
Reichert & Schön 2000	Reichert J. and Schön M. (2000) Methanemissionen durch den Einsatz von Gas in Deutschland von 1990 bis 1997 mit einem Ausblick auf 2010. Untersuchung für den Deutschen Verein des Gas- und Wasserfaches e.V., unter Mitarbeit von Lars Behnke. Fraunhofer-Institut für System-technik und Innovationsforschung (ISI), Karlsruhe.
Röder et al. 2004	Röder A., Bauer C. and Dones R. (2004) Kohle. 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, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Seifert 1998	Seifert M. (1998) Methanfreisetzung. In: Sonderdruck Nr. 1414, gwa 9/98, Schweizerischer Verein des Gas- und Wasserfaches (SVGW), Zü-rich, pp.
Snam 1999	Snam (1999) Health, Safety and Environment; 1998 Report. Snam Eni Group, Mailand.
Snam 2000	Snam (2000) Health, Safety and Environment; 1999 Report. (ed. Snam Eni Group), Mailand.
SVGW 2002	SVGW (2002) Zertifizierungsverzeichnis (Zulassungsliste) Gas 2002. Schweizerischer Verein des Gas- und Wasserfaches (SVGW), Zürich.
SWISSGAS 1999	SWISSGAS (1999) Eigenschaften der in der Schweiz verteilten Erdgase im Jahre 1998. Schweizerische Aktiengesellschaft für Erdgas, Zürich.
VSG 2001	VSG (2001) VSG-Jahresstatistik 2000. Verband der Schweizerischen Gasindustrie, Zürich.
WEG 2001	WEG (2001) Jahresbericht 2000: Zahlen & Fakten. Wirtschaftsverband Erdöl- und Erdgasgewinnung (WEG), Hannover.

6 Coal

Authors: Alexander Röder, Christian Bauer, Roberto Dones PSI

6.1 Modelled products

The main goal of this study is the quantification of the environmental burdens associated with the power production by coal plants in Europe. Additionally, heat systems, raw coal and processed coal products are available in the ecoinvent database, although the modelling of the chain my not be fully consistent with these coal products. The hard coal chain and the lignite chain are analysed separately. The most important step of the chains, i.e. power plants, has been addressed in a very detailed way, whereas other steps have been simplified. The following sections give an overview of the datasets available to the user.

6.1.1 Coal products

Hard coal is imported to Europe from all over the world. As hard coal mining conditions may greatly differ with the location, the production of raw coal has been modelled separately for the eight most important production regions worldwide: Australia, South Africa, Russia, East Asia, Eastern and Western Europe, North and South America. No differentation of coal products has been done at mining, although coal preparation has been included in the mine model to reflect average conditions in the eight regions. Contrary to hard coal, lignite is not transported over long distances because of its lower heating value, which implies mobilization of greater masses, and power plants are mine-mouth. Extraction of raw lignite has been modelled only for average European conditions, mostly for German conditon for which data were available. In NORDEL-countries peat is used for electricity production instead of lignite. Considering the need of somewhat modelling peat fired power plants for describing the country-specific electricity mixes, also peat extraction has been included in the database though using a simple extrapolation from lignite mining.

Processing of coal to derive different products has been modelled separately. The production of hard coal and lignite briquettes as well as lignite dust is analysed for average European conditions. Coke making with the byproducts coke oven gas, benzene, and tar is modelled for European and worldwide conditions.

6.1.2 Electricity production

Electricity production at hard coal and lignite power plants is modelled for all European countries where such plants are installed. Datasets for hard coal power plants are available for Austria, Belgium, Spain, Germany, France, Italy, The Netherlands, Portugal, Croatia, Czech Republic, Slovak Republic, and Poland. Datasets for lignite power plants are available for Austria, Spain, France, Greece, Germany, Slovenia, Bosnia-Herzegowina, Macedonia, Serbia and Montenegro, Hungary, Czech Republic, Poland, and Slovak Republic. Additionally, averages for UCTE, CENTREL, and NORDEL (the latter with peat instead of lignite) are available in the database, based on the production shares of coal plants in single European countries for year 2000.

6.1.3 Heat production

Heat production is modelled for two base cases: a stove with capacity between 5 kW and 15 kW, firing coke, hard coal or lignite briquettes and anthracite as fuels; and, an industrial furnace with a capacity in the range of 1 MW to 10 MW, fired with industrial hard coal.

6.2 System description

6.2.1 System boundaries

Fig. 6.1 and Fig. 6.2 show the flow charts with the modelled steps of the assessed lignite and hard coal systems. Lignite power plants are mine-mouth, thus lignite is directly transported with conveyor belt from the extraction site into the plant. On the contrary, hard coal may be transported over long distances and needs to be somewhat stored between extraction and use. For each step of the chains the relevant infrastructure has been modelled along with the ecoinvent standard approach, as shown in the figures.

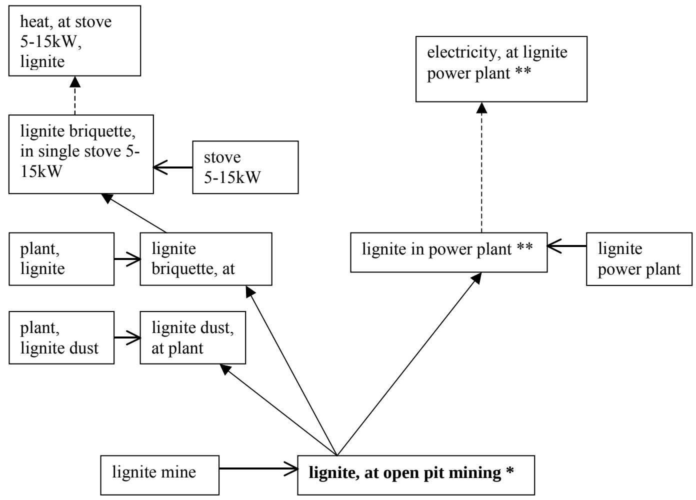

Fig. 6.1 Schematic picture of the modelled lignite chain.

* Modelled for average Europe; ** Modelled for AT, BA, CZ, DE, ES, FR, GR, HU, MK, PL, SI, SK, YU.

: flow of coal

: infrastructure requirement

: conversion into useful energy

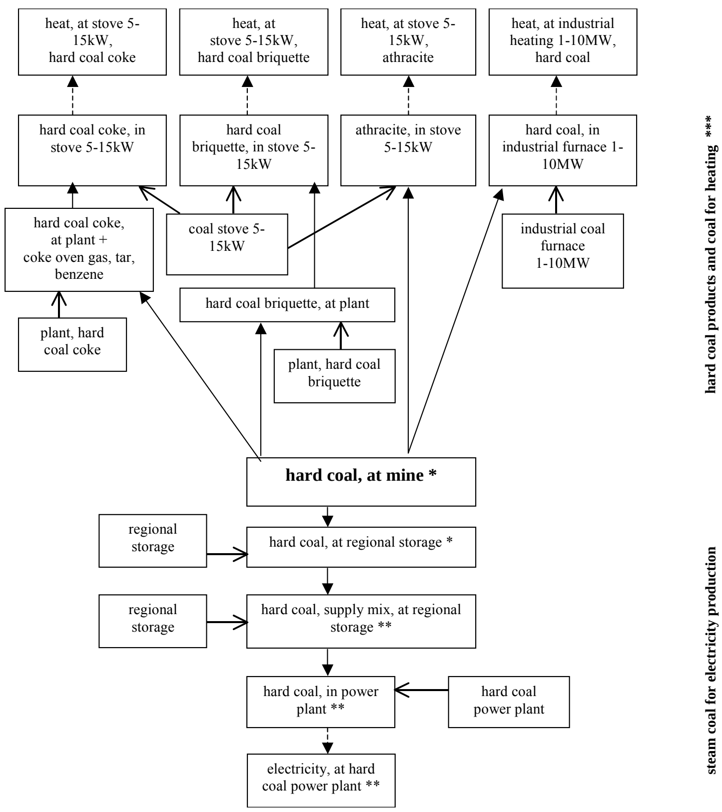

Fig. 6.2 Schematic picture of the modelled hard coal chain.

* Modelled for AU, ZA, WEU, EEU, RNA, RLA, RU, CPA; ** Modelled for AT, BE, CZ, DE, ES, FR, HR, IT, NL, PL, PT, SK, NORDEL; *** Modelled for average European conditions.

: flow of coal

: infrastructure requirement

: conversion into useful energy

6.2.2 Mining

Hard coal

Hard coal extraction is modelled for the eight most important mining regions worldwide. Coal washing is analysed together with extraction, as available data do not allow a seperation. Although the infrastructure of open pit and underground mines has been modelled separately, due to lack of specific information no differentiation could be made for the average operation of these two types of mining in the eight regions. Region-specific shares of open pit and underground mines are shown in Tab. 6.1. The models of the infrastructure include the most important materials like steel, concrete, explosives, or wood as well as energy requirements. Most of the base data represent German and Russian conditions. In general, the influence of mining infrastructure for cumulative results of produced hard coal is not relevant.

Tab. 6.1 Shares of open pit and underground mines for the modelled hard coal mining regions.

	Australia	East Asia	Russia	South Africa	Eastern Europe	Western Europe	North America	South America
open pit	0.68	0.03	0.33	0.5			0.58	1
underground	0.32	0.97	0.67	0.5	1	1	0.42	

Tab. 6.3 gives an overview of the most important operational data for hard coal mining in the eight modelled regions. Main source of information is (Hinrichs et al. 1999), a study on global hard coal mining. For ecoinvent v1.1, only one average worldwide heating value for the resource hard coal has been defined. This value is used for the calculation of the Cumulative Energy demand (CED) (see Frischknecht et al. 2003). In order to calculate a weighted average, available data on heating values of raw coal and yearly productions were used as shown in Tab. 6.2.

Tab. 6.2 Heating values of raw coal and yearly production of different mining regions.

	H_o, commercial coal	Raw coal	**H_o, Raw coal**			Yearly production
	MJ/kg	t/t SKE *	MJ/kg		MJ/kg	Mio. t SKE *
China	21.10	1.49	19.7	**East Asia**	**19.7**	799.2
India	20.80	1.48	19.8			176.2
USA	25.20	1.52	19.3	**North America**	**19.3**	732.3
Canada	27.83	1.50	19.5			59.0
South Africa	24.90	1.46	20.1	**South Africa**	**20.1**	166.4
Australia	26.37	1.46	20.1	**Australia**	**20.1**	164.3
Russia	23.44	1.69	17.3	**Russia**	**17.3**	140.5
Poland	24.90	1.90	15.4	**Eastern Europe**	**16.1**	113.6
Ukraine	20.00	1.70	17.2			60.7
Germany	27.00	2.00	14.7	**Western Europe**	**15.8**	52.3
Great Britain	24.10	1.69	17.3			39.4
				South America **	**19.1**	
				Average	**19.1**	

* 1 t SKE = 29.308 GJ
** Own assumption, no data available.

Tab. 6.3 Resource consumption, energy and material requirements, methane emissions, and tailings for mining in different hard coal extraction regions modelled in this study, per tonne of extracted raw coal.

		East Asia	North America	South Africa	Australia
Resource, hard coal, in ground	t	1.106	1.321	1.304	1.381
Resource, water (mining water?)	m^3	2.63	0.54	0.37	1.30
Electricity use	kWh	12.9	25.1	13.9	17.9
Heat use*	MJ	106.7	46.2	55.3	35.2
Water use	kg	442	355	206	180
Blasting	kg	0.125	1.131	1.480	1.625
Diesel	MJ	24.2	33.7	48.3	65.5
Disposal, hard coal tailings, in surface backfill	kg	155	415	270	309
Methane emissions to air	kg	6.6	3.0	3.5	2.7

		Russia	Eastern Europe	Western Europe	South America
Resource, hard coal, in ground	t	1.228	1.358	1.526	1.245
Resource, water (mining water?)	m^3	1.24	1.69	1.58	1.30
Electricity use	kWh	93.0	45.8	37.8	10
Heat use*	MJ	73.7	110.0	110.0	0
Water use	kg	503	514	486	200
Blasting	kg	0.767	0.076	0.035	2
Diesel	MJ	41.8	22.3	5.8	120.0
Disposal, hard coal tailings, in surface backfill	kg	271 *	271	461	250
Methane emissions to air	kg	9.2	8.2	13.6	0.2

* Assumed produced with an industrial hard coal furnace 1-10 MW.

Lignite

Lignite mining is modelled for average European conditions, using data from Germany, Austria, Greece, Former Yugoslavia, Czechia, and Spain in the 1980s and 1990s, which are shown in Tab. 6.4. Peat mining in NORDEL-countries is only addressed in first approximation using the average figures for lignite mining, whereas the heating value is peat specific. The model also includes the relevant infrastructure, which represents German and Russian conditions. In general, the influence of mining infrastructure for cumulative results of produced hard coal is not relevant.

Tab. 6.4 Energy consumption and methane emissions of lignite mining for average European conditions, per tonne of extracted coal.

		Europe
Electricity use	kWh	20
Diesel	kJ	15
Methane emissions to air	kg	0.23

6.2.3 Processing

Hard coal

Tab. 6.5 shows an overview of characteristics of hard coal coke and briquettes, based on data of German production plants from the late 1980s and early 1990s. The full list of trace elements can be found in the German report (Röder et al. 2004).

Tab. 6.5 Main characteristics of hard coal products addressed in this study.

		Hard coal coke	Hard coal briquettes
Bulk density	kg/m³	480-580	740-820
Heating value H_u	MJ/kg	28.6	31.4
Water content	%	6	4
Ash content	%	10	8.5
C	%	81.7	80
N	%	0.9	0.5
S	%	0.7	1
Cl	%	0.04	0.08
F	%	0.005	0.005

Hard coal coke

Coke production is a complex process with many byproducts and is not described here in details. Modelled byproducts of this study are coke oven gas, tar and benzene. Coke making has been modelled for European conditions, based on German data from the early 1990s, covering about 70% of the German coke production, and for worldwide conditions, based on data of the late 1980s from 25 coke plants operated in the USA. The allocation of all energy and material requirements as well as emissions to the byproducts taken into account in the modelling is based on the energy content of the produced coke, coke oven gas, benzene, and tar in German coke plants. The allocation factors, which are assumed to be the same for European and worldwide conditions, are shown in Tab. 6.6. Due to lack of data from the US plants, also material and energy requirements are assumed to be the same for European and worldwide conditions. Tab. 6.6 reports only the input raw coal and the electricity use.

Tab. 6.6 Hard coal input, electricity requirements and allocation factors used for the coking process.

Input	(relative to one t coke)		
	Hard coal [t/t coke]	1.38	
	Electricity [kWh/t coke]	48.5	
Output	(relative to one MJ coke)	MJ	%
	Coke	1	79
	Tar	0.052	4
	Coke oven gas	0.189	15
	Benzene	0.014	1
	Total	1.254	100

Tab. 6.7 shows key emission factors of the coking process used for this study. The full list of trace element emissions can be seen in the German report (Röder et al. 2004). The available data for the US coke plants (AP-42 2002) allow to distinguish between emissions from the two main possible configurations of the coke making plant: “Non-recovery” (of coke oven gas) and “Byproduct”. For most of the emission species, minimum and maximum values were available. For modelling a worldwide coking process,[4] the maximum values of the emissions from the “Byproduct” process have been chosen, because for most of the emitted species they are the largest. The underying assumption was that this set may give a picture of the coke plants around the world, for less strict environmental regulations than in the USA today can be expected (thus the use of US data form the 1980s). However, the choice of the “Byproduct” process also reflects current US conditions, where only one coke plant out of 25 was operating with the “Non-recovery” process in the year 1998.

[4] This was necessary within ecoinvent to model coke used in the average worldwide production of pig iron.

Tab. 6.7 Selected emission factors assumed for coking for European and worldwide conditions.

[kg/kg hard coal in coke plant]	Worldwide	Europe
Carbon dioxide	1.60E-01	8.69E-02
Carbon monoxide	1.70E-02	1.02E-03
Methane	2.63E-03	3.58E-05
Nitrogen oxides	8.47E-04	8.78E-04
NMVOC	1.05E-02	1.02E-04
Particulates, < 2.5 um	2.47E-03	5.15E-04
Particulates, > 10 um	4.16E-03	8.54E-04
Particulates, > 2.5 um, and < 10um	1.13E-03	2.42E-04
Sulfur dioxide	1.62E-03	4.39E-04

Hard coal briquettes

Key data of the production of hard coal briquettes are requirements of energy and basic materials as well as emissions to air during the production process, which are shown in Tab. 6.8. Additionally to the shown species, other trace element emissions can be found in the German report (Röder et al. 2004). Data are reflecting typical German production conditions at the beginning of the 1990s.

Tab. 6.8 Requirements of basic materials and energy as well as selected emissions from the production of hard coal briquettes.

		Hard coal briquettes
Requirements		
Hard coal	kg/MJ	0.0318
Bitumen	kg/MJ	0.00223
Heat *	MJ/MJ	0.0075
Electricity	kWh/MJ	0.000278
Emission species	kg/MJ	
Particulates, < 2.5 um		1.91E-05
Particulates, > 10 um		5.40E-06
Particulates, > 2.5 um, and < 10um		1.15E-05
Arsenic		2.90E-10
Cadmium		1.50E-11
Chromium		5.90E-10
Lead		1.20E-09
Mercury		2.90E-12
Zinc		1.50E-11

* Assuming produced by an industrial hard coal furnace 1-10 MW.

Lignite

Tab. 6.9 shows an overview of key characteristics of raw lignite, lignite briquettes, and lignite dust products. These data represent lignite processing at one plant in Germany, where briquettes, dust, and coke are produced, and reflect German conditions at the beginning of the 1990s.

Tab. 6.9 Main characteristics for lignite products addressed in this study.

		Raw lignite	Lignite briquettes	Lignite dust
Bulk density	kg/m^3		710-750	
Heating value H_u	MJ/kg	8.8	19.5	21.7
Water content	%	58	19	11
Ash content	%	2.5	4	4
C	%	27.1	53.2	58.8
N	%	0.3	0.6	0.7
S	%	0.2	0.35	0.35
Cl	%		0.025	0.028
F	%		0.001	0.0012

Key data for the production of lignite products shown in Tab. 6.10 are requirement of basic materials and energy as well as selected emissions during the production process. Complete emission data can be seen in the German report (Röder et al. 2004). Production data are based on information from one German plant assumed to be representative for average German production conditions at the beginning of the 1990s (Rheinbraun 1993). Electricity is assumed to be delivered by the modelled German lignite power plant.

Tab. 6.10 Requirements of basic materials and energy as well as selected emissions from the production of lignite briquettes and dust.

		Lignite dust	Lignite briquettes
Requirements			
raw lignite, at mining	kg/MJ	0.1114	0.1108
electricity, lignite, at power plant	kWh/MJ	2.89E-02	2.53E-02
Emission species	kg/MJ		
Particulates, < 2.5 um		5.30E-06	5.30E-06
Particulates, > 10 um		1.50E-06	1.50E-06
Particulates, > 2.5 um, and < 10um		3.20E-06	3.20E-06
Arsenic		1.10E-11	1.00E-11
Cadmium		1.40E-12	1.20E-12
Chromium		3.10E-11	2.80E-11
Lead		1.10E-11	1.00E-11
Mercury		2.20E-13	2.00E-13
Zinc		6.20E-11	5.70E-11

6.2.4 Transport and storage

Hard coal

To simplify the modelling, it is assumed that the extracted hard coal is stored at regional storages before it is transported to Europe. The data sets for transport and storage take into account rail transport, electricity consumption, land use, coal losses, particle emissions, and emissions to (ultimately) groundwater from the storage. Afterwards, the coal is transported to the single European countries, where it assumed to be delivered to another storage before being supplied to the power plants. The transport is modelled with freight ship, train, and lorry. A specific supply mix is modelled for each country, taking into account the import shares from the eight mining regions in year 2000 (Tab. 6.11). The storage in the countries consuming the coal takes into account land use, electricity consumption, particle emissions, and groundwater emissions. The data are not reported here because the storage steps have relatively low importance for the calculation of total burdens.

Tab. 6.11 Shares of the origin of hard coal, used in power plants for electricity production in European countries.

	Australia	East Asia	Russia	South Africa	Eastern Europe	Western Europe	North America	South America
AT	-				0.997	0.003		
BE	0.328	0.030	0.044	0.285	0.041	0.018	0.242	0.014
CZ					1.000			
DE	0.038	0.007	0.004	0.093	0.110	0.670	0.027	0.053
ES	0.067	0.097	0.042	0.265	0.016	0.390	0.095	0.030
FR	0.252	0.046	0.005	0.293	0.040	0.004	0.200	0.160
HR			0.100		0.900			
IT	0.191	0.117	0.051	0.219	0.036		0.273	0.113
NL	0.150	0.122	0.019	0.258	0.087	0.002	0.166	0.199
PL					1.000			
PT	0.123		0.001	0.262			0.158	0.460
SK			0.280		0.720			
UCTE	0.067	0.032	0.023	0.116	0.430	0.211	0.067	0.055

6.2.5 Power plants

Electricity production at ignite power plants is analysed for the UCTE countries Austria, Spain, France, Greece, Germany, Serbia, Bosnia-Herzgovina, Macedonia and Slovenia as well as for the CENTREL countries Czech Republic, Poland, Hungary and Slovak Republic. Average electricity production at lignite power plants in UCTE and CENTREL is modelled using the shares of these countries to total lignite electricity production in year 2000.

Electricity production at hard coal power plants is analysed for the UCTE countries Austria, Belgium, Germany, Spain, Italy, France, the Netherlands, Portugal, and Croatia as well as for the CENTREL countries Poland, Czech Republic, and Slovak Republic. UCTE and CENTREL hard coal electricity mixes are modelled using the shares of these countries to total hard coal electricity production in year 2000.

The modelling of the power plant step of the coal chain is based on a database containing data of about 700 hard coal and lignite power units in Europe, reflecting conditions around year 2000. The following items are available for each single power plant: capacity; gross and net efficiency; coal consumption; load factor; installation rate and efficiency of flue gas desulphurisation and de-NO_x; heating value, humidity, sulphur and ash content of the used coal; emission factors for SO_x, NO_x, particulates, and in some cases also for trace elements. This allows a complete and consistent modelling of hard coal electricity generation in Europe.

The modelling of the power plant infrastructure is based on two exemplary lignite and hard coal units with 100 MW and 500 MW power rate, respectively. Data of these plants are based on information from the 1980s about several hard coal and lignite power plants in Germany. The assumed share of 100 MW to 500 MW units is 30/70 for lignite and 10/90 for hard coal. Tab. 6.12 shows the material and energy requirements for the construction of the units.

Tab. 6.12 Material and energy requirements for the construction of lignite and hard coal power plants.

	100 MW				500 MW			
	Hard coal		Lignite		Hard coal		Lignite	
	ESP & FGD		ESP & FGD		ESP, FGD, & $DeNO_x$		ESP & FGD	
	t/MW	kg/TJ_{in}	t/MW	kg/TJ_{in}	t/MW	kg/TJ_{in}	t/MW	kg/TJ_{in}
Concrete	400	281	500	250	250	176	300	150
Steel total	100	70	130	65	80	56	100	50
Unalloyed steel	90	63	117	59	72	51	90	45
Low alloyed steel	9	6.3	11.7	5.9	7.2	5.1	9	4.5
High alloyed steel	1	0.7	1.3	0.7	0.8	0.6	1	0.5
Copper	1.5	1.1	1.5	0.8	1.3	0.9	1.3	0.7
Aluminium	1	0.7	1	0.5	0.6	0.4	0.6	0.3
Mineral wool	1	0.7	1	0.5	0.75	0.5	0.75	0.4
Plastics	1.5	1.1	1.5	0.8	1	0.7	1	0.5
		MJ/TJ_{in}		MJ/TJ_{in}		MJ/TJ_{in}		MJ/TJ_{in}
Electricity		90		80		70		60
Building machines		400		350		300		250
Oil heating		400		350		300		250

Key data for the environmental performance of coal power plant operation are the emission factors. Data for the main pollutants are shown in Tab. 6.13 to Tab. 6.18 for hard coal and lignite, together with the country-specific average effiencies of the plants, the requirements of country-specific hard coal supply mix, and the amounts of SO_x and NO_x retained with pollution control. Complete emission factors including trace elements can be found in the German report (Röder et al. 2004). CO_2 emissions are determined using information from country-specific literature. Emission parameters for SO_x, NO_x and particulates are calculated as country-specific averages with data from single power plants, taking into account installation rate and efficiency of emission control. Also the retained amounts of SO_x and NO_x are calculated in this way. Halogen emissions are calculated by using the concentrations in the coal mix used in single countries and element-specific transfer coefficients. CO emission rates, one average for hard coal and one for lignite plants, are determined by using various literature sources. Different sources are also used for methane and dioxine emissions, which are assumed to be the same per MJ_{in} for lignite and hard coal plants. The total mass of NMVOC emissions is calculated as an average from several literature sources then broken down into single substances using an emission profile (Corinair 1991) assumed to be valid for both hard coal and lignite. Emission factors for N_2O are calculated as averages from various literature sources. As the installation of de-NO_x leads to an increase of N_2O emissions, country-specific emissions of nitrous oxide take into account installation rates of de-NO_x at the power plants. Trace element emissions are calculated taking into account the country-specific elementary analysis of the coal, the element-specific retention factors, the country-specific efficiency of emission control, and the country-specific average particle emissions from coal power plants. Radioactive emissions are divided into radon, which is a gas, and isotopes of other elements, which are correlated to particle emissions. Specific emission factors take into account uranium, thorium, and kalium concentrations in country-specific hard coal mixes as well as the activities of the single isotopes. For radon emissions it is assumed that 80% of the radon contained in the coal ore are emitted at the power plant, 20% during mining. As there are no data available for lignite, it is assumed that the concentrations of the radioactive elements are one sixth of hard coal.

Tab. 6.13 Operational data of hard coal power plants in Austria, Belgium, Czechia, Germany, and Spain.

	Unit/MJ_{in}	AT	BE	CZ	DE	ES
Efficiency [%]		40.4	36.0	29.4	35.9	35.8
Hard coal supply mix	kg	4.51E-02	4.15E-02	4.52E-02	4.17E-02	4.23E-02
SOx retained, in hard coal flue gas desulphurisation	kg	5.46E-04	8.18E-05	5.35E-04	6.16E-04	1.18E-04
NOx retained, in SCR	kg	1.94E-04	1.34E-05		2.34E-04	3.09E-05
Emissions to air						
Carbon dioxide, fossil	kg	9.40E-02	9.48E-02	9.30E-02	9.22E-02	9.60E-02
Carbon monoxide, fossil	kg	8.00E-06	8.00E-06	8.00E-06	8.00E-06	8.00E-06
Dinitrogen monoxide	kg	3.90E-06	1.24E-06	5.00E-07	3.97E-06	8.90E-07
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	6.13E-05	1.57E-04	1.89E-04	6.21E-05	3.62E-04
Particulates, < 2.5 um	kg	2.72E-06	2.06E-05	5.02E-06	4.73E-06	4.85E-05
Particulates, > 10 um	kg	5.16E-06	6.21E-06	5.30E-06	5.28E-06	7.85E-06
Particulates, > 2.5 um, and < 10um	kg	3.20E-07	2.42E-06	5.90E-07	5.56E-07	5.70E-06
Sulfur dioxide	kg	4.62E-05	3.47E-04	7.80E-05	6.56E-05	7.31E-04

Tab. 6.14 Operational data of hard coal power plants in France, Croatia, Italy, and The Netherlands.

	Unit/MJ_{in}	FR	HR	IT	NL
Efficiency [%]		35.5	35.5	37.2	35.3
hard coal supply mix	kg	4.24E-02	4.52E-02	4.29E-02	4.32E-02
SOx retained, in hard coal flue gas desulphurisation	kg	9.16E-05	2.65E-04	3.22E-04	5.11E-04
NOx retained, in SCR	kg			3.64E-04	2.11E-04
Emissions to air					
Carbon dioxide, fossil	kg	9.30E-02	9.30E-02	9.40E-02	9.30E-02
Carbon monoxide, fossil	kg	8.00E-06	8.00E-06	8.00E-06	8.00E-06
Dinitrogen monoxide	kg	5.00E-07	5.00E-07	2.18E-06	3.20E-06
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	1.92E-04	2.81E-04	1.96E-04	7.86E-05
Particulates, < 2.5 um	kg	2.39E-05	1.22E-05	2.45E-05	1.82E-06
Particulates, > 10 um	kg	6.41E-06	5.72E-06	6.44E-06	5.11E-06
Particulates, > 2.5 um, and < 10um	kg	2.81E-06	1.43E-06	2.89E-06	2.14E-07
Sulfur dioxide	kg	4.45E-04	2.48E-04	3.92E-04	6.07E-05

Tab. 6.15 Operational data of hard coal power plants in Poland, Portugal, Slovakia, and NORDEL.

	Unit/MJ_{in}	PL	PT	SK	NORDEL
Efficiency [%]		33.2	37.5	38.4	41.6
hard coal supply mix	kg	4.53E-02	4.25E-02	4.50E-02	4.31E-02
SOx retained, in hard coal flue gas desulphurisation	kg	3.08E-04		2.17E-04	4.40E-04
NOx retained, in SCR	kg			5.21E-05	1.94E-04
Emissions to air					
Carbon dioxide, fossil	kg	9.30E-02	9.40E-02	9.30E-02	9.40E-02
Carbon monoxide, fossil	kg	8.00E-06	8.00E-06	8.00E-06	8.00E-06
Dinitrogen monoxide	kg	5.00E-07	5.00E-07	1.55E-06	3.90E-06
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	1.81E-04	2.62E-04	4.07E-04	6.13E-05
Particulates, < 2.5 um	kg	2.62E-05	1.46E-05	9.18E-05	2.72E-06
Particulates, > 10 um	kg	6.54E-06	5.86E-06	1.04E-05	5.16E-06
Particulates, > 2.5 um, and < 10um	kg	3.08E-06	1.72E-06	1.08E-05	3.20E-07
Sulfur dioxide	kg	6.44E-04	5.35E-04	5.75E-04	1.30E-04

Tab. 6.16 Operational data of lignite power plants in Austria, Bosnia-Hercegovina, Czechia, Germany, and Spain.

	Unit/MJ_{in}	AT	BA	CZ	DE	ES
Efficiency [%]		36.9	29.6	33.2	33.1	35.9
raw lignite, at mining	kg	8.62E-02	9.71E-02	8.93E-02	1.15E-01	9.52E-02
SOx retained, in lignite flue gas desulphurisation	kg	4.09E-04		2.27E-03	9.92E-04	1.09E-03
NOx retained, in SCR	kg	5.43E-04			2.02E-04	1.10E-05
Emissions to air						
Carbon dioxide, fossil	kg	1.05E-01	1.05E-01	1.05E-01	1.08E-01	1.05E-01
Carbon monoxide, fossil	kg	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Dinitrogen monoxide	kg	3.40E-06	5.00E-07	5.00E-07	2.59E-06	5.30E-07
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	6.45E-05	2.39E-04	2.11E-04	7.15E-05	3.01E-04
Particulates, < 2.5 um	kg	8.42E-06	1.19E-04	8.67E-06	4.85E-06	4.17E-05
Particulates, > 10 um	kg	5.50E-06	1.20E-05	5.51E-06	5.29E-06	7.46E-06
Particulates, > 2.5 um, and < 10um	kg	9.91E-07	1.40E-05	1.02E-06	5.70E-07	4.91E-06
Sulfur dioxide	kg	7.28E-05	1.89E-03	2.20E-04	5.27E-05	2.72E-03

Tab. 6.17 Operational data of lignite power plants in France, Greece, Hungary, Macedonia, and Poland.

	Unit/MJ_{in}	FR	GR	HU	MK	PL
Efficiency [%]		28.1	35.2	27.9	32.3	35.1
Raw lignite, at mining	kg	6.02E-02	1.94E-01	1.16E-01	1.33E-01	1.20E-01
SOx retained, in lignite flue gas desulphurisation	kg	6.63E-04	2.14E-04	5.22E-04		5.03E-04
Emissions to air						
Carbon dioxide, fossil	kg	1.08E-01	1.23E-01	1.05E-01	1.10E-01	1.05E-01
Carbon monoxide, fossil	kg	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Dinitrogen monoxide	kg	5.00E-07	5.00E-07	5.00E-07	5.00E-07	5.00E-07
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	1.13E-04	1.33E-04	2.59E-04	2.87E-04	1.52E-04
Particulates, < 2.5 um	kg	4.64E-06	8.84E-05	3.12E-05	7.48E-05	5.70E-05
Particulates, > 10 um	kg	5.27E-06	1.02E-05	6.84E-06	9.40E-06	8.36E-06
Particulates, > 2.5 um, and < 10um	kg	5.46E-07	1.04E-05	3.67E-06	8.80E-06	6.71E-06
Sulfur dioxide	kg	8.28E-05	5.85E-04	1.59E-03	2.45E-03	8.68E-04

Tab. 6.18 Operational data of lignite power plants in Slovenia, Slovakia, Yugoslavia, and NORDEL (peat).

	Unit/MJ_{in}	SI	SK	YU	NORDEL
Efficiency [%]		32.4	23.1	29.8	35.0
Raw lignite, at mining	kg	1.01E-01	9.90E-02	1.27E-01	
Peat, at mine	kg				1.14E-01
SOx retained, in lignite flue gas desulphurisation	kg	2.62E-04	1.02E-03		
NOx retained, in SCR	kg		1.40E-04		
Emissions to air					
Carbon dioxide, fossil	kg	1.05E-01	1.05E-01	1.08E-01	1.05E-01
Carbon monoxide, fossil	kg	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Dinitrogen monoxide	kg	5.00E-07	1.86E-06	5.00E-07	2.59E-06
Methane, fossil	kg	1.00E-06	1.00E-06	1.00E-06	1.00E-06
Nitrogen oxides	kg	2.58E-04	2.03E-04	1.88E-04	1.18E-04
Particulates, < 2.5 um	kg	4.34E-05	2.58E-05	1.88E-04	1.78E-05
Particulates, > 10 um	kg	7.55E-06	6.52E-06	1.61E-05	2.22E-06
Particulates, > 2.5 um, and < 10um	kg	5.10E-06	3.03E-06	2.21E-05	2.22E-06
Sulfur dioxide	kg	1.91E-03	9.94E-04	1.30E-03	1.98E-04

The ecoinvent dataset describing the operation of flue gas desulphurisation for hard coal plants takes into account the requirements of limestone and other materials, CO_2 emissions to air, and emissions to water, which are based on emission limits for Germany. The wastewater from lignite flue gas desulphurisation is used for humidification of the ash, therefore no net water emissions are taken into account. The dataset describing the catalytic nitrogen reduction in de-NO_x takes into account ammonia requirements and emissions to air. Details for these pollution control devices can be found in the German report.

Coal ash is modelled using country-specific average production rates (per TJ_{in}) and compositions. Additionally, country-specific recycling rates are taken into account. Hard coal ash, which is not recycled, is assumed to be disposed of in residual material landfill, whereas lignite ash is assumed to be disposed of as mine backfill. The recycled part is not inventoried.

6.2.6 Heating systems

In general, the importance of coal heating systems was decreasing during recent years. Therefore, the relevant modelling for the ecoinvent database was not substantially reworked from the 1996 edition of the study. The relevant ecoinvent datasets reflect the infrastructure and operation of installed average heating systems at the beginning of the 1990s in Western Europe, mostly in Germany. In general, available literature data on specific environmental flows, especially for emissions, can differ in orders of magnitude. Therefore, an assessment of single coal heating systems should take into account possible variations in the emissions of the analysed boilers.

Four hard coal and one lignite heating systems are modelled: a stove with a capacity in the range of 5 kW to 15 kW, fired either with hard coal coke, hard coal / lignite briquettes, or anthracite, and an industrial hard coal furnace with a capacity between 1 MW and 10 MW, fired with the average UCTE hard coal supply mix..

Tab. 6.19 gives an overview of the characteristics of the used fuels. Data are mostly averages from various sources, reflecting German conditions of the early 1990s.

Tab. 6.19 Main characteristics of the coal fuels used in heating systems.

		Lignite briquettes	Anthracite	Hard coal coke	Hard coal briquettes	Industrial hard coal
Bulk density	kg/m^3	710-750	700-780 **	480-580	740-820 *	720-800 *
Low heating value	MJ/kg	19.5	32.4	28.6	31.4	28.9
Water content	%	19	4	6	4	8.7
Ash content	%	4	5	10	8.5	7.5
C	%	53.2	83	81.7	80	73.2
N	%	0.6	1.2	0.9	0.5	0.8
S	%	0.35	0.95	0.7	1	0.8
Cl	%	0.025	0.06	0.04	0.08	0.15
F	%	0.001	0.005	0.005	0.005	0.005

Tab. 6.20 shows the main characteristics of the modelled heating systems and their key emission factors. Complete emission data including trace elements can be seen in the German report (Röder et al. 2004). CO_2 emissions as well as emissions of S, F, and Cl are calculated using the fuel characteristics in Tab. 6.19 and element- and fuel-specific transfer coefficients. Emissions of CO, SO_2, H_2S, NO_x, NMVOC, CH_4, particulates, and dioxins are estimated based on various literature sources from the late 1980s and early 1990s. SO_2 emissions are not only depending (stoichiometrically) on the sulphur content of the fuel, but also on the share of sulphur retained in the ash, which is much higher for lignite than for hard coal. Therefore, SO_2 emissions from the lignite briquette stove are significantly smaller than those from the hard coal heating systems. Emissions of trace elements from the industrial furnace are calculated using elementary concentrations, the water content of the fuels, and element-specific transfer coefficients, which are assumed to be the same as for power plants because no more appropriate information could be retrieved. Trace element emissions from the small stove have been extrapolated on the basis of the total particle emissions from the combustion of different fuels. Emission of radioactive isotopes are estimated on the basis of what estimated for power plants.

Tab. 6.20 Assumed efficiency, lifetime, load factor, and selected emission factors of the modelled heating systems.

		lignite briquettes	anthracite	hard coal briquettes	hard coal coke	hard coal industrial furnace
Efficiency	%	70	70	70	70	80
Lifetime	years	30	30	30	30	20
Load factor	h/year	1600	1600	1600	1600	5000
Emission species	kg/MJ_{in}					
Carbon dioxide, fossil		9.15E-02	8.00E-02	8.25E-02	9.50E-02	9.15E-02
Carbon monoxide, fossil		4.00E-03	8.00E-03	5.00E-03	5.00E-03	1.00E-04
Dinitrogen monoxide		5.00E-07	1.50E-06	1.50E-06	1.50E-06	1.00E-06
Methane, fossil		3.00E-04	1.80E-04	3.00E-04	1.50E-05	1.00E-05
Nitrogen oxides		1.00E-04	5.00E-05	5.00E-05	6.00E-05	2.00E-04
NMVOC		1.74E-05	3.45E-06	1.79E-05	7.50E-07	1.72E-06
Particulates, < 2.5 um		2.00E-05	5.00E-06	2.00E-05	5.00E-06	2.00E-05
Particulates, > 10 um		1.40E-04	3.50E-05	1.40E-04	3.50E-05	1.00E-05
Particulates, > 2.5 um, and < 10um		4.00E-05	1.00E-05	4.00E-05	1.00E-05	2.00E-05
Sulfur dioxide		1.00E-04	3.50E-04	4.50E-04	4.40E-04	5.00E-04

6.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2. Further results can be seen in the German report (Röder at al. 2004).

6.3.1 Selected results

Tab. 6.21 shows selected results of the modelled hard coal heating systems. In Tab. 6.22 through Tab. 6.25 selected cumulative results of electricity production at hard coal power plants for the analysed countries are presented. In Tab. 6.26 through Tab. 6.29 selected cumulative results of electricity production at lignite power plants for the analysed countries are shown.

Tab. 6.21 Selected LCI results and cumulative energy demand of the modelled hard coal heating systems.

		Name		heat, at hard coal industrial furnace 1-10MW	heat, anthracite, at stove 5-15kW	heat, hard coal briquette, at stove 5-15kW	heat, hard coal coke, at stove 5-15kW
		Location		RER	RER	RER	RER
		Unit	Unit	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.25E+00	1.26E+00	1.49E+00	1.99E+00
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	4.47E-02	2.18E-02	3.04E-02	4.99E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	6.85E-03	3.50E-03	4.89E-03	7.92E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.13E-03	5.41E-04	7.55E-04	1.24E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	6.55E-03	6.34E-03	6.73E-03	1.01E-02
LCI results							
resource	Land occupation	total	m2a	3.48E-03	3.78E-03	4.22E-03	6.04E-03
air	Carbon dioxide, fossil	total	kg	1.22E-01	1.20E-01	1.28E-01	1.51E-01
air	NMVOC	total	kg	1.98E-05	3.61E-05	1.57E-04	3.12E-05
air	Nitrogen oxides	total	kg	3.11E-04	1.33E-04	1.62E-04	2.48E-04
air	Sulphur dioxide	total	kg	6.71E-04	5.39E-04	7.06E-04	7.19E-04
air	Particulates, < 2.5 um	total	kg	2.84E-05	1.05E-05	6.10E-05	3.91E-05
water	BOD	total	kg	1.40E-05	1.61E-05	6.94E-05	3.23E-05
soil	Cadmium	total	kg	2.33E-12	3.76E-12	4.78E-12	6.23E-12
Further LCI results							
air	Dinitrogen monoxide	total	kg	1.59E-6	2.41E-6	2.59E-6	2.73E-6
air	Methane, fossil	total	kg	3.46E-4	5.95E-4	7.87E-4	5.50E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	2.90E-5	1.88E-5	8.11E-5	3.62E-5
air	Particulates, > 10 um	total	kg	1.29E-4	1.68E-4	3.34E-4	2.79E-4
air	Lead	total	kg	9.75E-8	1.57E-7	6.25E-7	1.65E-7
air	Zinc	total	kg	8.65E-9	2.34E-7	9.12E-7	2.41E-7
air	Radon-222	total	kBq	2.59E+0	1.26E+0	1.76E+0	2.89E+0
air	Polonium-210	total	kBq	1.08E-4	1.22E-4	4.89E-4	1.23E-4
water	Arsenic, ion	total, short term	kg	1.70E-7	1.24E-7	2.21E-7	2.79E-7
water	Arsenic, ion	ground-, long-term	kg	2.18E-11	1.70E-11	2.11E-11	3.42E-11
water	Cadmium, ion	total, short term	kg	1.70E-9	3.68E-9	4.75E-9	6.17E-9
water	Cadmium, ion	ground-, long-term	kg	2.89E-10	1.81E-10	2.78E-10	4.05E-10

Tab. 6.22 Selected LCI results and cumulative energy demand for electricity production at hard coal power plants in Austria, Belgium, Spain, and France.

		Name		electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant
		Location		AT	BE	ES	FR
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.13E+01	1.19E+01	1.22E+01	1.21E+01
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	2.56E-01	2.54E-01	1.94E-01	2.48E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.30E-02	4.15E-02	3.16E-02	4.11E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	6.23E-03	6.31E-03	4.80E-03	6.15E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	7.25E-02	3.79E-02	5.54E-02	3.46E-02
LCI results							
resource	Land occupation	total	m2a	3.83E-02	2.34E-02	3.18E-02	2.22E-02
air	Carbon dioxide, fossil	total	kg	8.85E-01	1.03E+00	1.01E+00	1.03E+00
air	NMVOC	total	kg	5.55E-05	1.58E-04	1.04E-04	1.68E-04
air	Nitrogen oxides	total	kg	8.15E-04	2.85E-03	4.33E-03	3.28E-03
air	Sulphur dioxide	total	kg	5.67E-04	4.34E-03	7.77E-03	5.39E-03
air	Particulates, < 2.5 um	total	kg	5.34E-05	2.56E-04	5.19E-04	2.97E-04
water	BOD	total	kg	9.80E-05	2.86E-04	1.64E-04	2.89E-04
soil	Cadmium	total	kg	1.85E-11	1.75E-11	2.87E-11	2.68E-11
Further LCI results							
air	Dinitrogen monoxide	total	kg	3.64E-5	1.73E-5	1.19E-5	1.03E-5
air	Methane, fossil	total	kg	3.38E-3	1.62E-3	3.25E-3	1.34E-3
air	Particulates, > 2.5 um, and < 10um	total	kg	1.16E-4	9.14E-5	1.09E-4	9.79E-5
air	Particulates, > 10 um	total	kg	1.03E-3	1.48E-3	1.33E-3	1.56E-3
air	Lead	total	kg	8.47E-8	1.32E-7	2.90E-7	2.64E-7
air	Zinc	total	kg	9.73E-8	2.70E-7	4.60E-7	1.13E-6
air	Radon-222	total	kBq	1.48E+1	1.47E+1	1.12E+1	1.44E+1
air	Polonium-210	total	kBq	2.30E-5	4.74E-4	1.34E-3	7.45E-4
water	Arsenic, ion	total, short term	kg	1.70E-7	1.45E-7	1.43E-6	2.30E-7
water	Arsenic, ion	ground-, long-term	kg	1.58E-9	1.55E-9	1.56E-9	1.58E-9
water	Cadmium, ion	total, short term	kg	2.20E-8	2.00E-8	2.21E-8	2.42E-8
water	Cadmium, ion	ground-, long-term	kg	5.33E-9	2.43E-9	2.71E-9	2.49E-9

Tab. 6.23 Selected LCI results and cumulative energy demand for electricity production at hard coal power plants in Italy, The Netherlands, Portugal, and Germany.

		Name		electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant
		Location		IT	NL	PT	DE
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.14E+01	1.21E+01	1.10E+01	1.25E+01
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	2.35E-01	2.42E-01	1.87E-01	1.79E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.91E-02	4.06E-02	3.15E-02	2.99E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	5.81E-03	6.00E-03	4.63E-03	4.43E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	3.77E-02	3.98E-02	2.06E-02	6.39E-02
LCI results							
resource	Land occupation	total	m2a	2.40E-02	2.49E-02	1.51E-02	3.53E-02
air	Carbon dioxide, fossil	total	kg	9.84E-01	1.03E+00	9.63E-01	9.67E-01
air	NMVOC	total	kg	1.45E-04	1.58E-04	1.53E-04	7.06E-05
air	Nitrogen oxides	total	kg	3.00E-03	2.03E-03	3.62E-03	1.03E-03
air	Sulphur dioxide	total	kg	4.50E-03	1.42E-03	5.72E-03	9.17E-04
air	Particulates, < 2.5 um	total	kg	2.85E-04	7.44E-05	1.84E-04	7.78E-05
water	BOD	total	kg	2.50E-04	2.75E-04	2.04E-04	1.10E-04
soil	Cadmium	total	kg	1.81E-11	1.91E-11	1.67E-11	1.34E-11
Further LCI results							
air	Dinitrogen monoxide	total	kg	2.56E-5	3.75E-5	9.79E-6	4.17E-5
air	Methane, fossil	total	kg	1.42E-3	1.46E-3	8.02E-4	4.48E-3
air	Particulates, > 2.5 um, and < 10um	total	kg	1.17E-4	1.19E-4	5.76E-5	1.13E-4
air	Particulates, > 10 um	total	kg	1.51E-3	1.60E-3	1.48E-3	1.17E-3
air	Lead	total	kg	1.13E-7	3.83E-8	6.83E-8	7.87E-8
air	Zinc	total	kg	1.87E-7	7.08E-8	1.59E-7	8.14E-8
air	Radon-222	total	kBq	1.36E+1	1.40E+1	1.08E+1	1.04E+1
air	Polonium-210	total	kBq	3.79E-4	2.10E-5	2.81E-4	3.80E-5
water	Arsenic, ion	total, short term	kg	1.35E-7	1.64E-7	1.02E-7	1.93E-7
water	Arsenic, ion	ground-, long-term	kg	1.58E-9	1.74E-9	1.43E-9	1.74E-9
water	Cadmium, ion	total, short term	kg	1.98E-8	2.15E-8	1.64E-8	1.57E-8
water	Cadmium, ion	ground-, long-term	kg	3.90E-9	5.42E-9	1.41E-9	5.64E-9

Tab. 6.24 Selected LCI results and cumulative energy demand for electricity production at hard coal power plants in Czechia, Croatia, and Poland.

		Name		electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant
		Location		CZ	HR	PL
		Unit	Unit	kWh	kWh	kWh
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.52E+01	1.28E+01	1.35E+01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.46E-01	3.03E-01	2.22E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.05E-02	5.02E-02	3.60E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	6.09E-03	7.41E-03	5.48E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	9.74E-02	8.07E-02	8.65E-02
LCI results						
resource	Land occupation	total	m2a	5.13E-02	4.24E-02	4.58E-02
air	Carbon dioxide, fossil	total	kg	1.18E+00	9.99E-01	1.04E+00
air	NMVOC	total	kg	6.17E-05	6.49E-05	5.61E-05
air	Nitrogen oxides	total	kg	2.55E-03	3.17E-03	2.18E-03
air	Sulphur dioxide	total	kg	1.11E-03	2.72E-03	7.09E-03
air	Particulates, < 2.5 um	total	kg	9.28E-05	1.54E-04	3.08E-04
water	BOD	total	kg	7.80E-05	9.81E-05	7.04E-05
soil	Cadmium	total	kg	2.03E-11	2.23E-11	1.92E-11
Further LCI results						
air	Dinitrogen monoxide	total	kg	7.58E-6	6.92E-6	6.78E-6
air	Methane, fossil	total	kg	4.60E-3	3.91E-3	4.09E-3
air	Particulates, > 2.5 um, and < 10um	total	kg	1.23E-4	1.07E-4	1.09E-4
air	Particulates, > 10 um	total	kg	1.37E-3	1.19E-3	1.20E-3
air	Lead	total	kg	9.00E-8	2.95E-7	1.64E-7
air	Zinc	total	kg	9.23E-8	3.45E-7	4.03E-7
air	Radon-222	total	kBq	1.43E+1	1.76E+1	1.28E+1
air	Polonium-210	total	kBq	2.58E-5	2.90E-4	3.35E-4
water	Arsenic, ion	total, short term	kg	4.88E-7	2.66E-6	3.56E-6
water	Arsenic, ion	ground-, long-term	kg	2.13E-9	1.71E-9	1.79E-9
water	Cadmium, ion	total, short term	kg	2.11E-8	2.47E-8	1.89E-8
water	Cadmium, ion	ground-, long-term	kg	7.13E-9	4.91E-9	4.68E-9

Tab. 6.25 Selected LCI results and cumulative energy demand for electricity production at hard coal power plants in Slovakia, UCTE, and NORDEL.

		Name		electricity, hard coal, at power plant	electricity, hard coal, at power plant	electricity, hard coal, at power plant
		Location		SK	UCTE	NORDEL
		Unit	Unit	kWh	kWh	kWh
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.15E+01	1.22E+01	1.12E+01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.87E-01	2.02E-01	1.55E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.71E-02	3.36E-02	2.55E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	7.05E-03	5.01E-03	3.85E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	6.98E-02	5.27E-02	5.71E-02
LCI results						
resource	Land occupation	total	m2a	3.71E-02	3.04E-02	3.14E-02
air	Carbon dioxide, fossil	total	kg	9.20E-01	9.88E-01	8.51E-01
air	NMVOC	total	kg	6.59E-05	1.05E-04	6.00E-05
air	Nitrogen oxides	total	kg	4.14E-03	2.26E-03	8.78E-04
air	Sulphur dioxide	total	kg	5.59E-03	3.25E-03	1.35E-03
air	Particulates, < 2.5 um	total	kg	8.89E-04	2.05E-04	4.63E-05
water	BOD	total	kg	9.35E-05	1.71E-04	8.71E-05
soil	Cadmium	total	kg	2.08E-11	1.86E-11	1.10E-11
Further LCI results						
air	Dinitrogen monoxide	total	kg	1.65E-5	2.91E-5	3.55E-5
air	Methane, fossil	total	kg	3.66E-3	3.18E-3	4.01E-3
air	Particulates, > 2.5 um, and < 10um	total	kg	1.77E-4	1.08E-4	7.40E-5
air	Particulates, > 10 um	total	kg	1.21E-3	1.32E-3	1.02E-3
air	Lead	total	kg	6.22E-7	1.35E-7	6.84E-8
air	Zinc	total	kg	7.78E-7	2.63E-7	6.42E-8
air	Radon-222	total	kBq	1.67E+1	1.17E+1	9.00E+0
air	Polonium-210	total	kBq	2.09E-3	3.91E-4	1.94E-5
water	Arsenic, ion	total, short term	kg	9.51E-7	4.15E-7	1.74E-7
water	Arsenic, ion	ground-, long-term	kg	1.56E-9	1.66E-9	1.45E-9
water	Cadmium, ion	total, short term	kg	2.18E-8	1.87E-8	9.98E-9
water	Cadmium, ion	ground-, long-term	kg	3.81E-9	4.32E-9	3.76E-9

Tab. 6.26 Selected LCI results and cumulative energy demand for electricity production at lignite power plants in Austria, Spain, Republic of Yugoslavia, and France.

		Name		electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant
		Location		AT	ES	CS	FR
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	8.55E+00	1.01E+01	1.55E+01	7.77E+00
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	9.09E-02	1.07E-01	1.55E-01	8.32E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.46E-02	1.81E-02	2.33E-02	1.42E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.31E-03	2.70E-03	3.97E-03	2.09E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	2.54E-03	2.79E-03	4.23E-03	2.21E-03
LCI results							
resource	Land occupation	total	m2a	1.67E-03	1.90E-03	2.91E-03	1.52E-03
air	Carbon dioxide, fossil	total	kg	1.04E+00	1.07E+00	1.33E+00	1.40E+00
air	NMVOC	total	kg	3.24E-05	4.55E-05	4.21E-05	3.66E-05
air	Nitrogen oxides	total	kg	7.16E-04	3.12E-03	2.41E-03	1.53E-03
air	Sulphur dioxide	total	kg	7.60E-04	2.73E-02	1.58E-02	1.10E-03
air	Particulates, < 2.5 um	total	kg	9.92E-05	4.47E-04	2.29E-03	8.27E-05
water	BOD	total	kg	3.33E-05	1.66E-04	3.36E-05	2.34E-05
soil	Cadmium	total	kg	6.15E-12	5.54E-12	7.68E-12	4.58E-12
Further LCI results							
air	Dinitrogen monoxide	total	kg	3.36E-5	5.80E-6	6.69E-6	6.76E-6
air	Methane, fossil	total	kg	2.27E-4	2.62E-4	3.93E-4	2.06E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	7.51E-5	2.14E-4	2.77E-4	1.37E-4
air	Particulates, > 10 um	total	kg	4.68E-4	6.45E-4	8.28E-4	5.25E-4
air	Arsenic	total	kg	3.49E-8	3.12E-8	2.08E-7	1.59E-8
air	Zinc	total	kg	4.53E-8	1.36E-7	1.33E-6	5.22E-8
water	Arsenic, ion	total, short term	kg	5.13E-6	2.24E-6	3.48E-6	1.83E-6
water	Arsenic, ion	ground-, long-term	kg	7.29E-11	7.71E-11	9.91E-11	7.66E-11
water	Cadmium, ion	total, short term	kg	5.59E-9	6.28E-9	6.91E-9	6.02E-9
water	Cadmium, ion	ground-, long-term	kg	3.62E-8	2.73E-7	4.19E-7	2.23E-7

Tab. 6.27 Selected LCI results and cumulative energy demand for electricity production at lignite power plants in Greece, Germany, Bosnia-Herzegovina, and Czech Republic.

		Name		electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant
		Location		GR	DE	BA	CZ
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.99E+01	1.27E+01	1.19E+01	9.72E+00
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.97E-01	1.31E-01	1.21E-01	1.06E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.99E-02	2.17E-02	1.82E-02	2.04E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	5.05E-03	3.31E-03	3.09E-03	2.60E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	5.40E-03	3.56E-03	3.29E-03	2.76E-03
LCI results							
resource	Land occupation	total	m2a	3.71E-03	2.41E-03	2.26E-03	1.88E-03
air	Carbon dioxide, fossil	total	kg	1.28E+00	1.20E+00	1.30E+00	1.16E+00
air	NMVOC	total	kg	4.23E-05	3.80E-05	3.89E-05	3.48E-05
air	Nitrogen oxides	total	kg	1.52E-03	8.97E-04	3.02E-03	2.38E-03
air	Sulphur dioxide	total	kg	6.05E-03	6.36E-04	2.30E-02	2.42E-03
air	Particulates, < 2.5 um	total	kg	9.25E-04	8.41E-05	1.46E-03	1.44E-04
water	BOD	total	kg	3.89E-05	3.42E-05	2.84E-05	2.63E-05
soil	Cadmium	total	kg	9.39E-12	7.13E-12	6.20E-12	5.39E-12
Further LCI results							
air	Dinitrogen monoxide	total	kg	5.91E-6	2.88E-5	6.61E-6	5.85E-6
air	Methane, fossil	total	kg	4.99E-4	3.25E-4	3.06E-4	2.51E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	1.47E-4	1.71E-4	1.79E-4	3.72E-4
air	Particulates, > 10 um	total	kg	9.52E-4	7.49E-4	6.36E-4	8.52E-4
air	Arsenic	total	kg	1.02E-7	1.19E-8	1.26E-7	1.58E-8
air	Zinc	total	kg	5.41E-7	3.26E-8	7.89E-7	4.50E-8
water	Arsenic, ion	total, short term	kg	4.65E-6	1.20E-6	2.71E-6	1.21E-6
water	Arsenic, ion	ground-, long-term	kg	1.08E-10	8.96E-11	8.71E-11	7.97E-11
water	Cadmium, ion	total, short term	kg	6.96E-9	6.39E-9	6.37E-9	5.87E-9
water	Cadmium, ion	ground-, long-term	kg	5.66E-7	3.04E-8	3.29E-7	1.47E-7

Tab. 6.28 Selected LCI results and cumulative energy demand for electricity production at lignite power plants in Hungary, Macedomia and Poland.

		Name		electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant
		Location		HU	MK	PL
		Unit	Unit	kWh	kWh	kWh
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.51E+01	1.49E+01	1.24E+01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.53E-01	1.49E-01	1.26E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.42E-02	2.23E-02	1.99E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.89E-03	3.81E-03	3.21E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	4.15E-03	4.06E-03	3.42E-03
LCI results						
resource	Land occupation	total	m2a	2.85E-03	2.79E-03	2.35E-03
air	Carbon dioxide, fossil	total	kg	1.38E+00	1.24E+00	1.10E+00
air	NMVOC	total	kg	4.38E-05	3.93E-05	3.54E-05
air	Nitrogen oxides	total	kg	3.48E-03	3.31E-03	1.68E-03
air	Sulphur dioxide	total	kg	2.06E-02	2.73E-02	9.00E-03
air	Particulates, < 2.5 um	total	kg	4.29E-04	8.46E-04	6.09E-04
water	BOD	total	kg	3.43E-05	3.19E-05	2.80E-05
soil	Cadmium	total	kg	7.65E-12	7.32E-12	6.28E-12
Further LCI results						
air	Dinitrogen monoxide	total	kg	7.09E-6	6.17E-6	5.68E-6
air	Methane, fossil	total	kg	3.84E-4	3.77E-4	3.17E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	1.54E-4	1.06E-4	1.52E-4
air	Particulates, > 10 um	total	kg	8.14E-4	7.13E-4	6.79E-4
air	Arsenic	total	kg	4.44E-8	1.24E-7	7.44E-8
air	Zinc	total	kg	1.80E-7	7.46E-7	5.53E-7
water	Arsenic, ion	total, short term	kg	3.51E-6	3.39E-6	2.23E-6
water	Arsenic, ion	ground-, long-term	kg	1.02E-10	9.33E-11	8.30E-11
water	Cadmium, ion	total, short term	kg	7.22E-9	6.44E-9	5.83E-9
water	Cadmium, ion	ground-, long-term	kg	4.28E-7	4.12E-7	5.80E-7

Tab. 6.29 Selected LCI results and cumulative energy demand for electricity production at lignite (peat) power plants in Slovenia, Slovak Republic, UCTE and NORDEL.

		Name		electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, lignite, at power plant	electricity, peat, at power plant
		Location		SI	SK	UCTE	NORDEL
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.13E+01	1.56E+01	1.37E+01	1.18E+01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.15E-01	1.64E-01	1.40E-01	1.19E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.78E-02	2.76E-02	2.25E-02	1.79E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.93E-03	4.13E-03	3.55E-03	3.04E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	3.12E-03	4.42E-03	3.80E-03	3.24E-03
LCI results							
resource	Land occupation	total	m2a	2.14E-03	3.00E-03	2.59E-03	2.22E-03
air	Carbon dioxide, fossil	total	kg	1.18E+00	1.67E+00	1.21E+00	1.10E+00
air	NMVOC	total	kg	3.60E-05	5.18E-05	3.97E-05	3.46E-05
air	Nitrogen oxides	total	kg	2.97E-03	3.32E-03	1.49E-03	1.32E-03
air	Sulphur dioxide	total	kg	2.11E-02	1.56E-02	6.95E-03	2.09E-03
air	Particulates, < 2.5 um	total	kg	4.99E-04	4.46E-04	5.07E-04	1.96E-04
water	BOD	total	kg	2.67E-05	4.35E-05	4.72E-05	2.66E-05
soil	Cadmium	total	kg	5.85E-12	8.94E-12	7.29E-12	5.97E-12
Further LCI results							
air	Dinitrogen monoxide	total	kg	6.03E-6	2.97E-5	1.98E-5	2.72E-5
air	Methane, fossil	total	kg	2.89E-4	4.03E-4	3.49E-4	3.01E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	1.06E-4	2.89E-4	1.79E-4	3.03E-5
air	Particulates, > 10 um	total	kg	5.94E-4	9.96E-4	7.67E-4	5.08E-4
air	Arsenic	total	kg	5.51E-8	3.87E-8	5.15E-8	1.10E-8
air	Zinc	total	kg	2.84E-7	1.42E-7	2.78E-7	2.81E-8
water	Arsenic, ion	total, short term	kg	2.64E-6	2.12E-6	2.14E-6	1.12E-6
water	Arsenic, ion	ground-, long-term	kg	8.14E-11	1.19E-10	9.17E-11	7.97E-11
water	Cadmium, ion	total, short term	kg	5.90E-9	8.75E-9	6.50E-9	5.65E-9
water	Cadmium, ion	ground-, long-term	kg	3.21E-7	2.58E-7	1.88E-7	2.84E-8

6.3.2 Analysis

In Fig. 6.3 through Fig. 6.5 cumulative emissions of CO_2, SO_2, and PM_{10} are presented for electricity production at the modelled hard coal power plants. In Fig. 6.6 through Fig. 6.8 the same emissions are shown for electricity production at the modelled lignite power plants. The cumulative emissions of electricity production are separated into direct contributions from the operation of the power plants, contributions from the infrastructure of the power plants, emissions control at the power plant, and the rest of emissions calculated for the power plant as well as contributions from coal transport and storage (only for hard coal) and mining. Fig. 6.9 through Fig. 6.11 show cumulative emissions of CO_2, SO_2, and PM_{10} for the unit of heat delivered by the modelled heating systems. Cumulative emissions are separated into direct operational contributions, contributions from the infrastructure of the boilers, fuel transport, ash disposal, and contributions from the upstream chain.

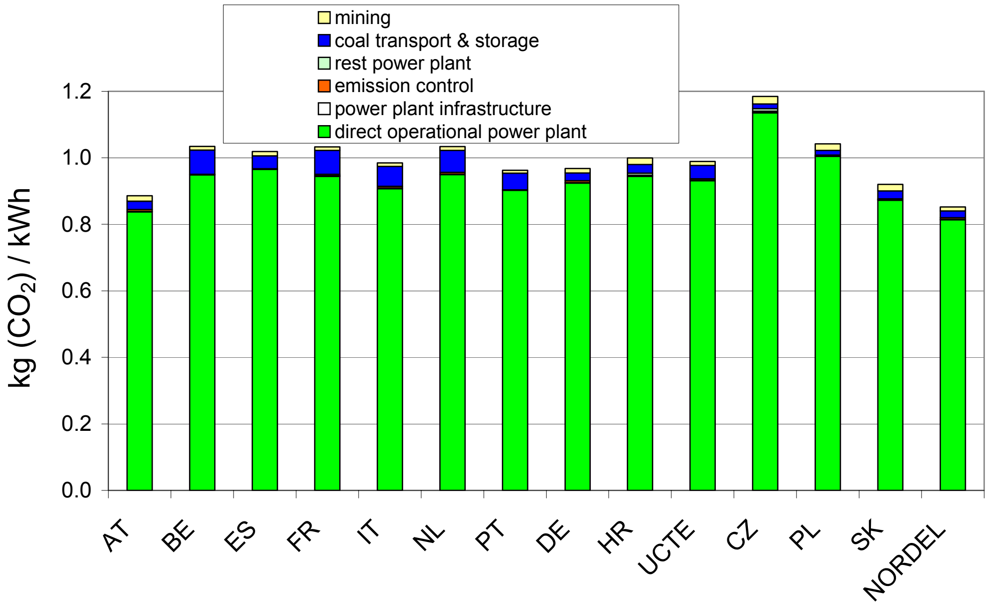

Fig. 6.3 Cumulative CO_2 emissions of electricity production at the modelled hard coal power plants.

Cumulative CO_2 emissions from electricity production at hard coal power plants are within the range 850 g (CO_2) / kWh for NORDEL to 1180 g (CO_2) / kWh for the Czech Republic. They are dominated by the direct operational emissions of the power plants and therefore nearly proportional to theor average efficiency. Transport contributes up to about 7%, depending on the share of overseas coal.

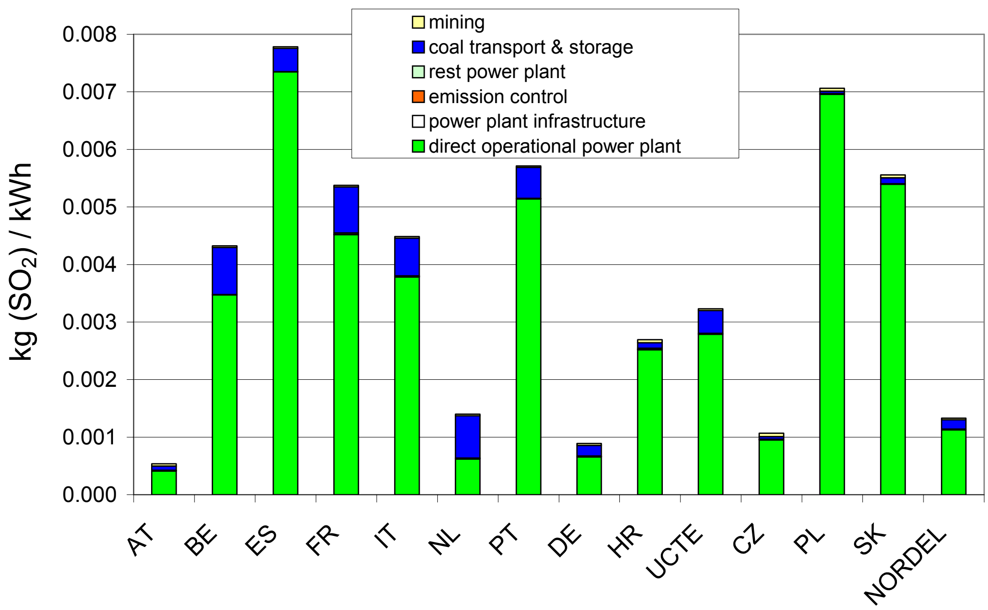

Fig. 6.4 Cumulative SO_2 emissions of electricity production at the modelled hard coal power plants.

Cumulative SO_2 emissions are between 0.5 g (SO_2) / kWh in Austria and 8 g (SO_2) / kWh in Spain. The large discrepancies are mostly caused by different direct operational emissions, which depend on the sulphur content of the coal and the installed scrubbers. Transport only contributes significantly in case of high shares of imported overseas coal.

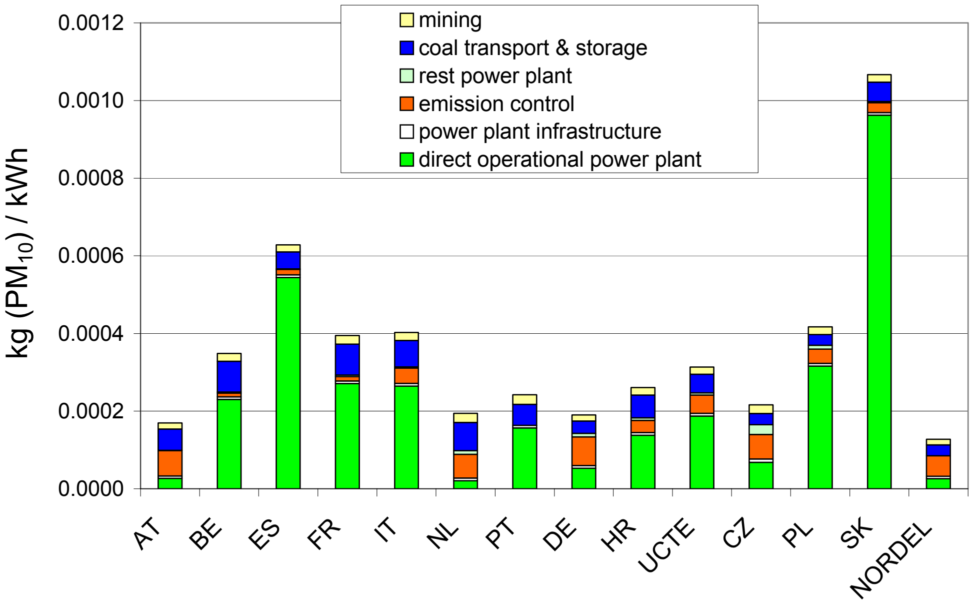

Fig. 6.5 Cumulative PM_{10} emissions of electricity production at the modelled hard coal power plants.

Cumulative PM_{10} emissions show a rather complex behaviour and are in the range 0.1 g ($PM_{2.5}$) / kWh for NORDEL to 1.1 g ($PM_{2.5}$) / kWh for the Slovak Republic. In case of high installation rates of highly efficient electrostatic precipitators (ESP) at the power plants, direct operational emissions contribute only very little to cumulative PM_{10} emissions. Indirect emissions from flue gas desulphurisation are important for countries with a high installation rate of this emission control. These indirect emissions originate in the production of limestone, which is used as feed material for flue gas desulphurisation. In case of high overseas imports, also transport contributes significantly to cumulative PM_{10} emissions. This fact becomes even more evident in case of countries with efficient emission control at power plants.

Differences in the results for coal production in the eight modelled regions are caused prevailently by the different energy requirements for mining operations. The direct methane emissions strongly depend on local characteristics.

Fig. 6.6 **Cumulative CO_2 emissions of electricity production at the modelled lignite power plants.**

For lignite chains, cumulative CO_2 emissions are in the range of about 1040 g (CO_2) / kWh in Austria to 1670 g (CO_2) / kWh in Slovak Republic. Besides the direct operational emissions, which are proportional to the efficiency, the other contributions are nearly negligible.

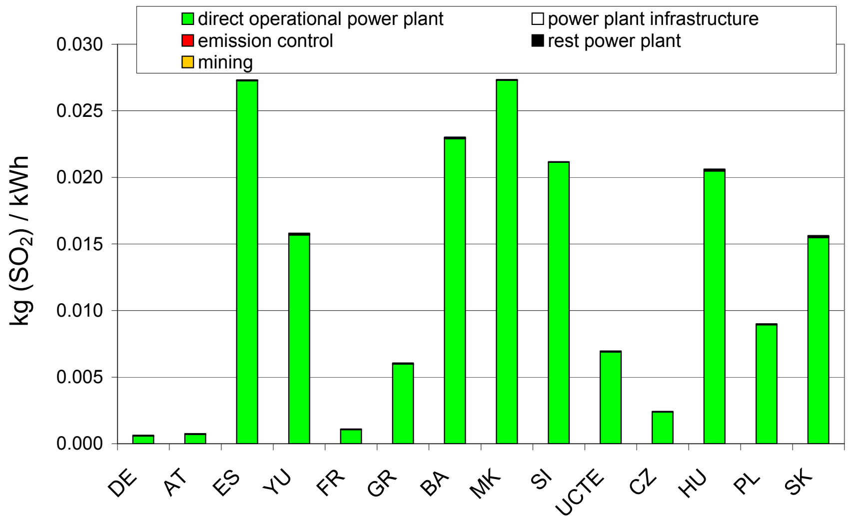

Fig. 6.7 **Cumulative SO_2 emissions of electricity production at the modelled lignite power plants.**

Cumulative SO_2 emissions are between 0.6 g (SO_2) / kWh in Germany and about 27 g (SO_2) / kWh in Spain and Macedonia. Similarly to hard coal, the large differences for country-specific averages are due to the sulphur content of lignite and the installation rate of scrubbers. Other contributions than direct operational emissions are negligible.

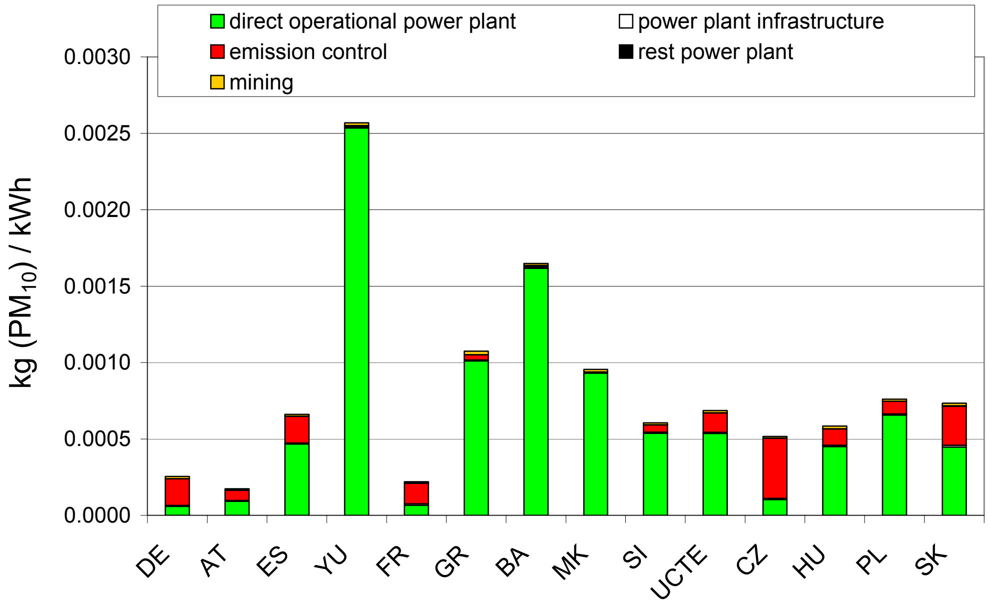

Fig. 6.8 Cumulative PM_{10} emissions of electricity production at the modelled lignite power plants.

There are two important contributions to cumulative PM_{10} emissions from lignite chains, which are in a range between 0.2 g (PM_{10}) / kWh in Austria and about 2.7 g (PM_{10}) / kWh in Yugoslavia: direct operational emissions, which depend on the installation of particle filters, and indirect PM_{10} emissions from scrubbers, which originate in mining of limestone. The latter are even dominating in countries with high rate of installation of highly efficient ESP and high retention of SO_2.

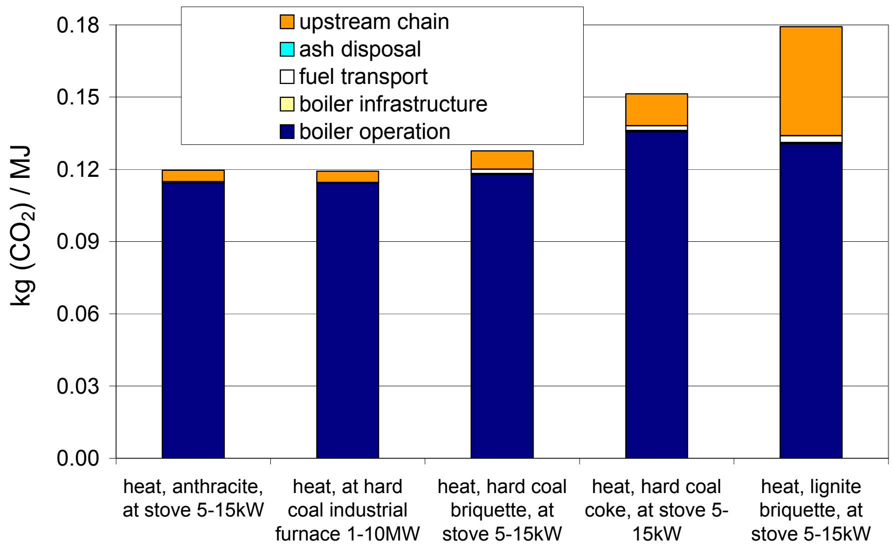

Fig. 6.9 Cumulative CO_2 emissions of heat production at the modelled heating systems.

In general, direct operational contributions dominate the cumulative CO_2 emissions of the modelled heating systems. These contributions mostly depend on the heating value of the fuel and on the efficiency of the furnace. Only the heating by lignite briquettes produces significant CO_2 emissions via the upstream chain, as much electricity is required for the production of the briquettes. Therefore, cumulative CO_2 emissions of this system are the highest among the modelled systems.

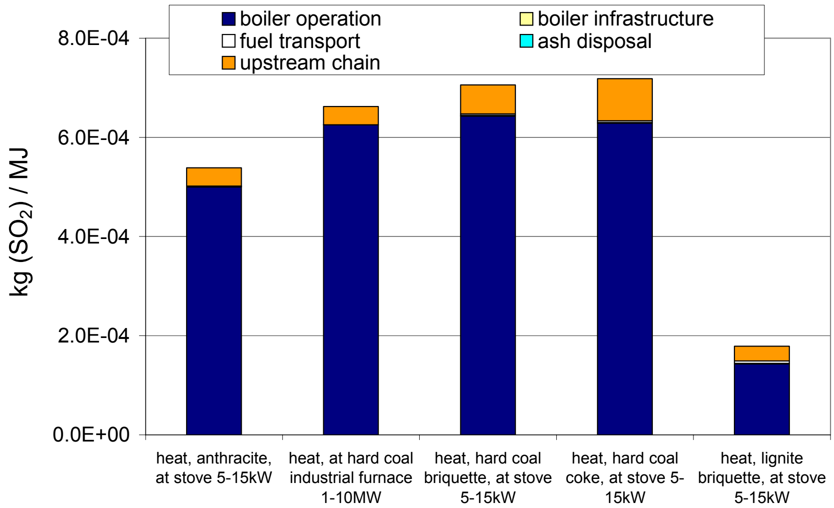

Fig. 6.10 Cumulative SO_2 emissions of heat production at the modelled heating systems.

Cumulative SO_2 emissions of the modelled hard coal fired heating systems are dominated by direct operational emissions. Compared to hard coal systems, the boilers burning lignite briquettes exhibit lower direct SO_2 emissions. The reason is that only briquettes with low sulphur content are assumed to be used and that the share of sulphur retained in the ash is much higher for lignite (ca. 70%) than for hard coal (ca.5%).

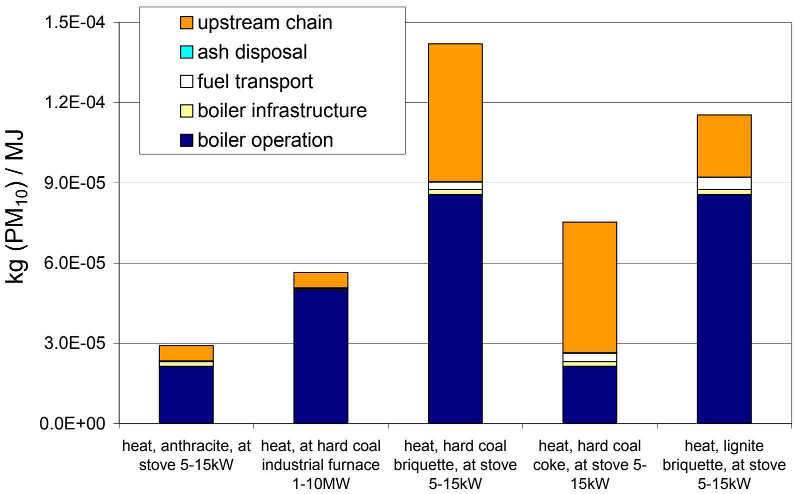

Fig. 6.11 Cumulative PM_{10} emissions of heat production at the modelled heating systems.

Due to its low operational emissions and no processing of the fuel, the anthracite stove has the lowest cumulative PM_{10} emissions. Operational emissions of the coke stove are similar, but substantial particulates, which dominate the cumulative result, are emitted during coke production. The hard coal and lignite briquette stoves have the highest PM_{10} emissions among the modelled heating systems, as both emissions from operation and briquette production are high.

6.4 Conclusion and outlook

In case of electricity production with hard coal, the cumulative LCI results show that the factors exhibiting the highest imfluence on key air emission species are the installation rate and average efficiency of emission control, the net effiency of the power plants, and the origin of the coal fired in the power plants. Coal transport can contribute significantly to single emissions, if the share of imported overseas coal is high. In relative terms, these contributions are increasing with decreasing direct power plant emissions. In case of lignite power plants, the contributions of coal transport to cumulative emissions are negligible, as power plants are mine-mouth. Another interesting fact is, that in case of high retention rates of SO_2, indirect particle emissions due to mining of limestone are high and can dominate the cumulative PM_{10} emissions.

The database covering about 700 European coal power units has been update to year 2000 or around it. For future updates, emission and efficiency data of power plants should be reviewed mostly for those countries, in which old power plants will be refurbished or closed and in which new or advanced coal technology will be installed. The modelling of the upstream chain is not as detailed as the analysis of the power plants, but it should be adequate for the focus of this study on power plants. Further work could be perform upon a different description of the chains for steam coal and other coal products, which could not be performed in this study. This would possibly correct the current little mismatch between the heating values of the country-specific hard coal supply mixes and the coal actually supplied to power plants. Another factor, which should be addresses in the future, is the modelling of long-term emissions into groundwater during coal extraction and from mine tailings.

6.5 References

AP-42 2002 — U.S. Environmental Protection Agency (EPA) (2002) AP-42, Fifth Edition, Volume I Chapter 1: External Combustion Sources. Bituminous and Subbituminous Coal Combustion. Downloaded from http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s01.pdf (8.4.2003).

Corinair 1991 — Veldt C. (1991) Corinair Inventory "Default Emission Factors (VOC Profiles)", Draft report. Commission of the Eueropean Community, Stand September 1991.

Frischknecht et al. 2003 — Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Hischier R., Hellweg S., Humbert S., Margni M., Nemecek T. and Spielmann M. (2003c) 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.

Hinrichs et al. 1999 — Hinrichs W., Atmaca T., Neumann W., Thormann A. (1999) Stoffmengenflüsse und Energiebedarf bei der Gewinnung ausgewählter mineralischer Rohstoffe. Teistudie Steinkohle. Bundesanstalt für Geowissenschaften und Rohstoffe, Staatliche geologische Dienste in der Bundesrepublik Deutschland. Hannover, Germany.

Rheinbraun 1993 — Rheinbraun AG (1993) Zahlen-Daten 91/92. Köln.

Röder et al. 2004 — Röder A., Bauer C. and Dones R. (2004) Kohle. 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-VI. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.

7 Nuclear

Author: Roberto Dones, PSI

7.1 Modelled nuclear systems

This study aims at modelling the nuclear cycles associated with power generation at Light Water Reactors (LWR) currently installed in Western Europe, with focus on the largest Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) installed in Switzerland: Gösgen and Leibstadt, respectively, both of the 1000 MW class. The above models have been extrapolated to describe the nuclear cycles in the countries with the highest nuclear share in UCTE, i.e. France and Germany, as well as the UCTE average.

Compared to the previous editions of this study, recycling of plutonium from reprocessing in mixed-oxide (MOX) fuel has been modelled using a static approach, i.e. taking into account the equilibrium production of plutonium in the reactor. The model and data used in the former versions of this study have been basically preserved for the steps: Mining, Conversion, Enrichment via diffusion, Fuel Fabrication, and Interim Storage. The reason is that the priority for the partial review work was given to the steps of the nuclear energy chain more important from the point of view of environmental burdens normalized to the unit electricity, or marked by important changes in recent years: Milling, Enrichment via centrifuge, Power Plant, Reprocessing, Spent Fuel Conditioning (newly addressed), and geological Final Repositories. The reference year is 2000, but several data describe time intervals around that year or relate to older sources if considered still applicable or defensible.

In spite of the partial update, the entire work can be seen as a sufficiently complete and accurate picture to describe the spectrum of environmental burdens associated with the unit of electricity of nuclear origin supplied to the Swiss and European grids, and allow comparisons with other energy systems.

7.2 System description

7.2.1 System boundaries

Fig. 7.1 gives a schematic overview of the modelled nuclear energy chains. For nearly all shown processes, a basic dataset to describe infrastructure (construction and decommissioning) has been defined. However, the principle that the contaminated wastes from decommissioning shall be attributed to the operation of the facility rather that to the infrastrucre itself has been systematically applied throughout the modelling. Key information on single steps are provided in the following sections, but complete data can be found in the German report.

7.2.2 Mining

No consideration of chemical mining (In-Situ Leaching, ISL, combining mining and milling in one step, nowadays producing about 30% of total uranium extracted world-wide) has been attempted because of objective difficulties in terms of resources for addressing an activity that presents a high variety of geological conditions and scanty literature on environmental impacts. The major harm from the uranium ore extraction & treatment industry is from milling. Therefore lower priority has been given to conventional mining in comparison to milling. It is worth noting that open pit and underground mining are always coupled with milling in the same area, and often mining and milling are merged in descriptions and environmental assessments. However, emissions to groundwater from ISL during operation may have substantial local impact. Although incomplete, the current modelling of conventional mining and milling should still represent a useful picture of the environmental burdens of the entire uranium extraction industry.

The modelling of uranium mining for ecoinvent, mostly based on several US references of the early 1980 still believed to be applicable today, includes: two datasets describing the "Infrastructure" for underground and open pit mining; two datasets describing the "Operation" of underground and open pit mines; and, one dataset describing the average wordldwide mix of natural uranium produced by underground and open pit mines at the beginning of the 2000s, attaining 60% and 40%, respectively. Tab. 7.1 shows the radioactive emissions to air and water during operation assumed in this study, after several US references.

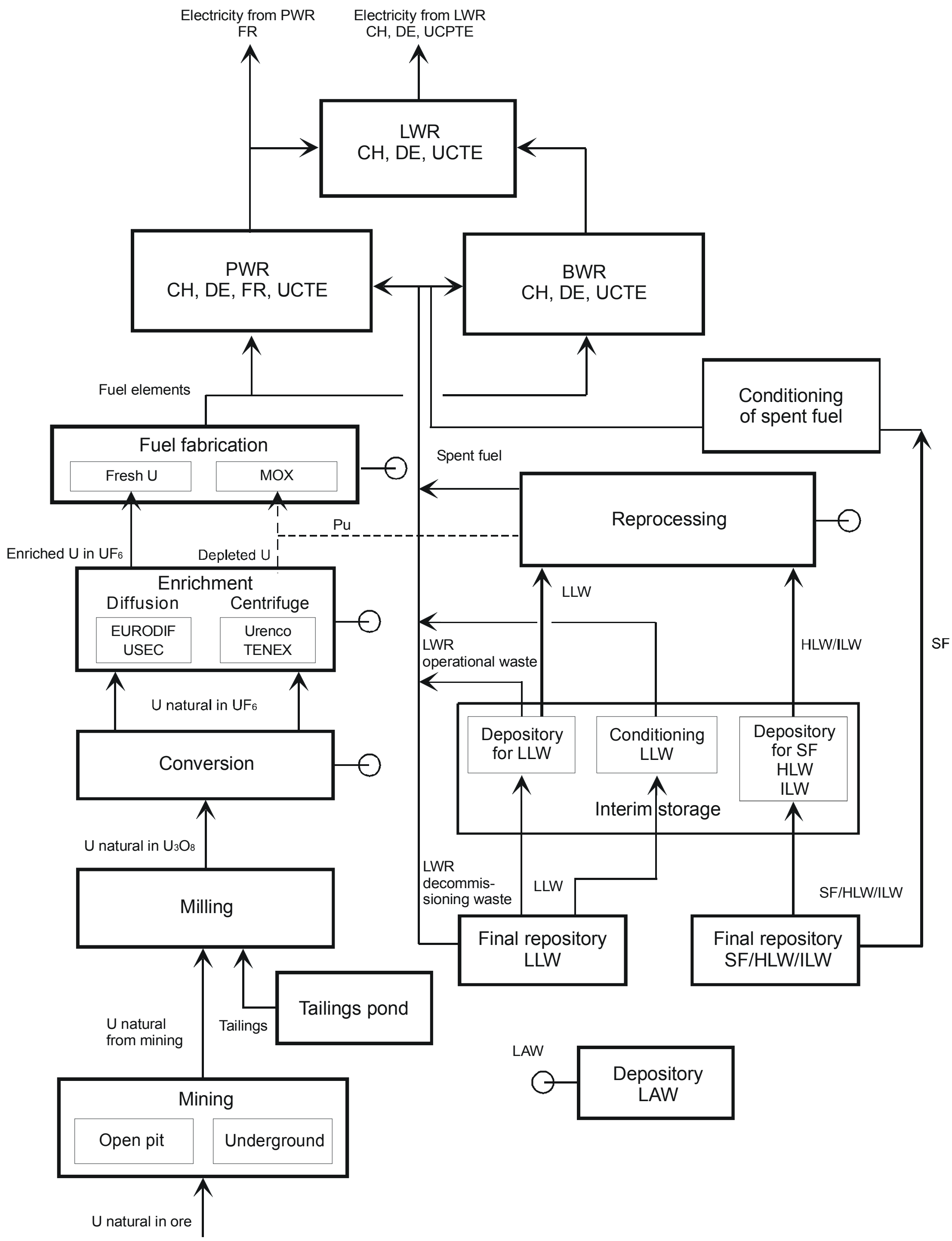

Fig. 7.1 Schematic overview of the modelled nuclear cycles.

Tab. 7.1 Summary of radioactive emissions to air and water during operation of conventional uranium mines assumed in this study.

[kBq/kgU$_{Output}$]	Underground	Open pit
To Air:		
U-α	2.3E+1	9.4E-2
Rn-222	1.0E+6	1.3E+5
Ra-226	1.3E+1	-
To Water:		
U-α	3.1E+2	2.2E+2
Ra-226	1.6E+3	5.0E+3
Th-230	3.0E+2	4.6E+2

7.2.3 Milling

Considering its importance for what concerns the long-term radioactive emissions of gaseous radon to air from the tailing ponds, relevant parts of the assessment of milling have been reworked in order to reflect recent knowledge. However, general data on the infrastrucure and operation of plants using the acid leaching process were not updated. This should not imply major consequences on the validity of the overall assessment, because already in the previous editions it was performed in a conservative manner (i.e., inclusiveness to the extent possible of burdens gathered from the literature). Moreover, fundamental changes in the practice of uranium milling are not expected, and if any environmental regulation has been implemented in recent years, this would lead to a local reduction of the burdens. It can be expected that the uncertainties of the available data, the variability of ore composition, and the actual conditions in several sites, which may dramatically differ from each other, would overshadow the importance of single pieces of information on specific items or mills. In other words, though the present cannot claim to be a study on current average uranium milling practice worldwide, nevertheless it should be sufficient for capturing the order of magnitude of main potential harms. However, while trying to minimize arbitrariness, some aspects had to be addressed developing simple models for which possibly conservative assumptions have been taken.

Furthermore, again because of the limited scope of this update, no resources have been spent on the modelling of long-term emissions (>100 years) to groundwater from tailings after closure of the mill. Also in a few other datasets of different industrial sectors within the ecoinvent database these emissions have not been modelled. Therefore, users should be careful at comparying the calculated total emissions to groundwater from different energy systems. The short-term (<100 years) emissions to groundwater have been roughly estimated using the average composition of a few US uranium mill tailings from (Dreesen et al. 1982) and assuming that 1% of all species will be released with the exception of highly soluble elements like Ca, Cl, K, Mg und Na (5%).

Milling has been modelled with three datasets describing the infrastructure, operation, and tailings. Here, only the long-term emission of radon is shortly described, whilst the interested reader will find the full analysis in the German report.

From an interval of 50 - 1150 kg(tailings)/kgU found in the literature, this study assumes an average of about 500 kg(tailings)/kgU, converted to the specific volume of 0.25 m^3(tailings)/kgU. Tab. 7.2 and Tab. 7.3 show the central figures for the estimation of the long-term emission of radon. Tab. 7.2 summarizes the data after (Senes 1998, EPA 1983) for the major mills around the world. In the same table, the mills are categorized (with some approximations) according to three climatic conditions. For the calculation of the average, the single radon fluxes are weighted with the area of the tailing ponds and the total production of each mill. It is worthy noting that according to (EPA 1983) a typical background flux for radon emissions is 0.037 Bq/m^2s. Other references give an interval 0.001-0.1 Bq/m^2s, but uraniferous areas may show values up to 50 Bq/m^2s (UI 1995). The 1983 EPA "Standards for Remedial Actions at Inactive Uranium Processing Sites" (UMTSP 1986) require that after reclamation the radon flux from tailings of closed US uranium mills shall be lower than 0.74 Bq/m^2s.

Tab. 7.2 Summary of key parameters for the tailing ponds of the most important uranium mills world-wide, categorized by climatic zones, after (Senes 1998, EPA 1983).

		Climatic category [a]	Tailings-area [m^2/kg U]	Radon flux [$Bq/m^2/s$]	Total Production U [t]	Operational lifetime [year]
Akouta	NE	1	0.0057	8.0	87000	52
Arlit	NE	1	0.0077	4.0	65000	52
Ranger	AU	2	0.0036	0.002	176000	59
Key Lake	CA	2	0.0013	0.0	180000	30
Rabbit Lake	CA	2	0.0026	0.0	54000	16
Cluff Lake	CA	2	0.0100	7.0	28000	26
Olympic Dam	AU	3	0.0260	0.2	278000	63
Rössing	NA	3	0.0520	1.2 [b]	144000	58
US operating mill	US	3	0.0700	0.74	32000	k.A.

[a] Legend: 1 = tropical; 2 = temperate; 3 = semi-arid.
[b] With no reclamation.

Tab. 7.3 Summary of the estimated average radon fluxes from uranium mill tailing ponds for three different climatic zones worldwide.

Climatic zone	% of world uranium production 1990-2030	Surface of tailing ponds (m^2/kgU)	Average and interval of the radon fluxes from non restored US facilities (Bq/m^2s)	Interval [c] of radon flux from restored and non restored facilities over 10^4 Jahren (Bq/m^2s)	Assumed radon flux for tailing ponds (Bq/m^2s)
after (NEA 1984)	after (Senes 1998)	after (Senes 1998)	(UMTSP 1986)	(NEA 1984)	after (Senes 1998)
1 tropical	15 %	0.007	NA	0.013 - 0.4	**6**
2 temperate	42 %	0.003	7 (0.05 - 26)	0.005 - 10	**1.52**
3 semi-arid	43 %	0.037	13 (0.04 - 106)	$3 \cdot 10^{-6}$ - 10	**0.71**

[c] The minimum corresponds to the most efficient reclamation.

Considering an average surface for tailings worldwide of approximately 0.018 m^2/kgU and 80000 year integration time (half life of the Rn-222 parent isotope Th-230, with which radon is in equilibrium) the long-term emission of radon is estimated at about **$3.5 \cdot 10^7$ kBq/kgU**.

7.2.4 Conversion

Due to the relatively low importance of the conversion step to the total burdens of the nuclear chain, the two datasets describing the infrastructure and the operation of US plants (in particular Sequoyah, closed since 1993) using the wet process to convert yellocake (U_3O_8) to UF_6 has not been updated from the previous version of this Study (1996). Therefore, considering that on the one hand the wet process leads to greater environmental burdens than the dry process, and on the other hand the current environmental regulations are presumably strictier than for the late 1980s, an overestimation of the assessed environmental burdens can be expected.

7.2.5 Enrichment

Under the constraint of static conditions and fixed parameters necessary in the ecoinvent datasets to represent any process, the four average enrichment levels used for nuclear fuel elements in the herewith modeled UCTE nuclear power plants (4.2%, 4.0%, 3.9%, and 3.8% in U-235) must be analysed separately.

It is also very important for the assessment of total burdens from the modelled chains to properly include the mixes of services from the main enrichment companies: Eurodif (FR) and USEC (US), using the highly energy consuming diffusion process; and Urenco (DE, NL, UK) and TENEX (RU) using centrifuge. The above is necessary not only to reflect the greatly different energy requirements for the two processes (factor greater than 50) but also the origin of the supply of electricity to individual factories.

In summary, enrichment has been modelled with the following datasets:

- 2 infrastructure datasets, one for each of the above mentioned processes;
- 4×4 datasets describing operation, including a set of 4 for each of the above mentioned Companies, for the 4 enrichment levels required; and,
- 8 datasets to describe the enrichment service mixes (see Tab. 7.4).

Neither the production of HF, recovered from the conversion of the depleted uranium from uranium esafluoride into uranium oxide, nor the production of depleted uranium, used in RepU fuel elements (see power plant section below) or in military applications for the great hardness of the oxide, have been considered. The above means that the environmental burdens are allocated entirely to the enriched uranium.

With respect to the 1996 edition of this study, the requirements and emissions of the Urenco plants have been updated using a recent environmental report (Urenco 2000), and the enrichment service mixes have been newly estimated to reflect conditions around year 2000.

Enrichment services

All LWRs in UCTE require about 8.8 MSWU/a (SWU stays for Separative Work Unit). This study assumes that 5.16 Mio. UTA/a from Eurodif supply all French PWRs, the entire production of Urenco Gronau (DE) of 1 Mio. UTA/a supplies German LWRs, and the entire production of Urenco Almelo (NL) of 1.5 Mio. UTA/a supplies LWRs in UCTE. For the remaining requirements, the following “Market-Mix” is assumed, using the residual production of Eurodif and Urenco Capenhurst as well as the limit of 20% imposed on Russian enrichment (Tenex):

Eurodif	USEC	Urenco	TENEX
29%	20%	32%	19%

The calculated supply mixes of enrichment services are shown in Tab. 7.4. Tab. 7.5 shows an overview of the assumption for average enrichment and the corresponding calculated separative work.

Tab. 7.4 Assumed supply mixes of enrichment services.

Modelled nuclear power plants	Burn-up $MW_{th}d/kgU$	Enrichnent % U^{235}	Share of enrichment services (%)			
			Diffusion		Centrifuge	
			EurodifF	USEC	Urenco	TENEX
PWR CH	53	4.2	**60**	—	**40**	—
PWR DE	50	4.0	**14**	**10**	**67**	**9**
PWR FR	42.8	3.8	**100**	—	—	—
PWR UCTE	45	3.9	**62**	**3**	**33**	**3**
BWR CH	48.6	3.8	**55**	**13**	**20**	**12**
BWR DE	48	4.0	**14**	**10**	**67**	**9**
BWR UCTE	48	4.0	**62**	**3**	**33**	**3**
LWR CH [a]	—	—	**58**	**6**	**31**	**5**
LWR UCTE [a]	—	—	**62**	**3**	**33**	**3**

[a] Weighted with the electricty production of the component BWrs and PWRs.

Tab. 7.5 Enrichment, separative work and natural uranium requirements for the modelled cycles.

Key factors		PWR				BWR		
		CH	DE	FR	UCTE	CH	DE	UCTE
Average enrichment of product	% U^{235}	4.2	4.0	3.8	3.9	3.8	4.0	4.0
Tails (depleted)	% U^{235}	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Separative work	$kgSWU/kgU_{enr}$	6.12	5.72	5.31	5.52	5.31	5.72	5.72
Specific requirements of	kgU_{nat}/ kgU_{enr}	8.76	8.31	7.87	8.09	7.87	8.31	8.31
natural uranium	$kgU_{nat}/kgSWU$	1.43	1.45	1.48	1.47	1.48	1.45	1.45
Depleted uranium	$kgU_{depl}/kgSWU$	1.27	1.28	1.29	1.29	1.29	1.28	1.28

Electricity use and supply source for the operation of the enrichment facilities

1. The electricity supply of 2400 kWh per kg of separative work unit (SWU) to the diffusion Eurodif plant in Tricastin (FR) is directly from nuclear power plants on the same site. The facility is water-cooled.
2. The electricity supply to the USEC diffusion plant still in operation, Paducah (USA), is directly from coal power plants on the same sites (Mohrhauer, 1995; Paducah, 1982). For the calculation, the average hard coal power plant in Poland has been assumed in first approximation, because of similar characteristics of the coal in the two cases. The assumed electricity intensity is 2600 kWh/kgSWU. The facility is still cooled with CFC-114, leaking at an assumed rate of about 0.02 kg/kgSWU.[5]
3. The electricity intensity for all centrifuge Urenco plants (DE, NL, UK) is about 40 kWh/kgSWU (Urenco 2000), assuming supply from the UCTE grid. Since 2000, no CFC is used in Gronau (DE) but R134a, leaking at an estimated small rate of $2.6 \cdot 10^{-4}$ kg/kgSWU. The same has been assumed for all Urenco plants
4. The electricity supply to TENEX (RU) centrifuge plants is assumed in first approximation to be from the CENTREL electricity mix. The electricity intensity as well as all other requirements and emissions are arbitrarily assumed to be the double of Urenco's.

[5] Information from (Trowbridge 1991) and http://www.antenna.nl/wise/466/4631.html, retrieved in im June 2003.

7.2.6 Fuel fabrication

In the present edition of this study, mixed-oxide (MOX) fuel elements, using reprocessed plutonium in PuO_2 and depleted uranium in UO_2 from enrichment, are considered to be used together with fresh uranium elements in LWRs. Fabricating MOX fuel elements implies more stringent requirements on safety and control of environmental emissions. However, the description of this step has not been updated, although the previous editions of this study were based on quite old data (1980-1984) on fabrication of fuel elements using enriched uranium from natural origin only. The reason is that fuel fabrication is included in the group of processes with the lowest environmental burdens per unit of electricity.

Although the MOX fuel fabrication plant is treated separately from the fabrication plant using fresh UO_2, the same dataset is practically used for both due to lack of specific information on the former. The only important difference is that the fuel fabrication plant handling uranium from natural sources is linked to the upstream chain, while the MOX fuel fabrication plant is neither charged of the upstream chain of natural uranium nor of the burdens from reprocessing directly.

7.2.7 Power plant

Two datasets describe the infrastructure (construction and decommissioning phases) of the Swiss PWR Gösgen (KKG) and BWR Leibstadt (KKL) of the 1000 MW class. Five other datasets were extrapolated from the above two, to represent the reactors of the same tape and class in Germany, France, and UCTE. No inventory has been performed for the 1300 MW class reactors, which produce about half of the total nuclear energy in France and about 80% in Germany.

Eight datasets describe the operation of PWRs and BWRs in Western Europe. Additional to the seven combinations of reactor type and country mentioned above (see Tab. 7.5), one dataset describes the Swiss PWR in case that only centrifuge enrichment from Urenco would be used, to characterize a representative nuclear cycle with the minimum total electricity requirement. The material and energy requirements as well as the production of solid wastes of the datasets for Germany, France and average UCTE have been estrapolated from the Swiss data. The current policies for the reprocessing of all (assumed for France) or partial (CH, DE) spent fuel from the entire lifetime of the installed plants have been accounted for, although there might be somewhat contradiction for the plutonium balance (total reprocessed from domestic spent fuel versus total employed in MOX fuel). From the approximations described above, it is recommended to avoid use of the power plant datasets and the final inventory results for comparisons of country-specific LWRs and associated cycles. Nevertheless, the results can be used to give meaningful intervals for the current European nuclear cycles associated with the installed LWR. The radioactive emissions to air and water from all nuclear power plants in UCTE have been taken consistently from one comprehensive publication of the European Union (Van der Stricht & Janssens 2001). The time interval considered for averaging the emissions is 1995-1999. The time interval considered for averaging the emissions is 1995-1999, but up to year 2002 for the Swiss units (BAG 1996-2003).

Three datasets have been defined for the mix of nuclear power plants (PWR & BWR) in Switzerland, Germany, and average UCTE (France has only PWRs).

Tab. 7.6 shows some key data for KKG and KKL. Tab. 7.7 reports the average capacity factors for country-specific LWRs between 1997 and 2001. The utilization factors of the infrastructure during operation for the modelled LWRs have been calculated from the Swiss figures taking into account the load factors (proportional to the electricity production over the assumed lifetime of 40 years) and the mass differences for the various sizes of the plants. They are in the range $2.9 \cdot 10^{-12}$ to $3.8 \cdot 10^{-12}$ kWh^{-1}. The masses and energy requirements for the construction of KKG and KKL are provided in Tab. 7.8.

Tab. 7.6 Key operational data of KKG and KKL.

	KKG	KKL
Start commercial operation	30 Oct.1979	15 Dec.1984
Lifetime (assumed)	40 years	40 years
Thermal/Electric Gross/Net capacity (rounded)	*since 1.1.1996:* 3002/1020/970 MW	*since 26.8.2002:* 3600/1220/1165 MW
Assumed average net yearly production (rounded)	7.78 E09 kWh	8.65 E09 kWh
Total net production during the lifetime (rounded)	3.11 E11 kWh	3.46 E11 kWh

Tab. 7.7 Average capacity factors for country-specific LWRs between 1997 and 2001.

	Net electricity production [kWh]	Average capacity factor [%]
	1997-2001	in 1997-2001 [a]
CH	1.29E+11	88.7
DE	8.31E+11	84.6
FR	1.95E+12	71.7
UCTE	4.31E+12	80.4

Tab. 7.8 Material and energy requirements for the construction of KKL and KKG.

		KKG	KKL
		[t]	[t]
Steel			
Total components (high alloyed)		21'911	20'440
Structural steel (low alloyed)		5'570	5'570
Reinforcing bars (unalloyed)		33'680	40'030
Copper		1'473	1'473
Titanium			130.6
Aluminium		200	200
Concrete	*[m^3]*	*169'200*	*200'200*
Fibre cement		5'300	5'300
Oil		200	200
Wood	*[m^3]*	*6'720*	*8'000*
Paper		850	4'250
		[m^3]	[m^3]
Overburden for foundations		8.5E+4	1.0E+6 [b]
		[TJth]	[TJth]
Light oil in heating		27	46
Light oil in industrial heating			130

[b] Due to the limit imposed to the height of the cooling tower in Leibstadt, a huge volume needed to be excavated. For the datasets BWR DE and BWR UCTE this factor has been inventoried as 1.0E+5 m^3.

The utilization of fuel elements of all sorts for the supply of one unit of electric energy to the grid can be calculated as:

$$\text{Fuel requirement in [kgU/kWh]} = \{\text{Burn-up in } [MW_{th}\cdot\text{day/kgU}] \times 24 \times 1000 \times \text{Net efficiency}\}^{-1}$$

where the burn-up in MW_{th}·day is the thermal energy developed in 24 hours operation at rated power.

Depending on the nuclear reactor fuel management, the uranium equivalent in fuel elements for LWR may be composed of: enriched uranium in UO_2 from mining of natural uranium; mixed oxides of Pu and U for MOX fuel elements; Highly Enriched Uranium (HEU) from dismantled warheads mixed with recycled uranium from reprocessing to make “RepU” fuel elements. The requirement of fresh uranium as well as uranium in RepU is assumed to be linked with the upstream chain through uranium enrichment to the adequate average level. For the static approach applied in ecoinvent, the plutonium and the depleted uranium are not loaded with the environmental burdens from the steps producing them. However, all cumulative burdens from reprocessing are attributed to the processed spent fuel and all cumulative burdens from the enrichment step are attributed to the production of enriched uranium. The modeling here proposed considers RepU fuel as it were using uranium from natural sources, i.e. as it were enriched for direct use in commercial power plants.

For the definition of the reference average burn-up for KKG, information on the finally discharged fuel elements from the reactor cycles 21 through 23 for the years 2000 to 2002 has been used. An average of 4.2% enrichment is estimated for fresh fuel, 4.4% if MOX fuel were also included. In recent years, the in-core average enrichment considering all types of fuel elements (fresh uranium, MOX, and RepU) is about 4.5%. The calculated average burn-up for all finally discharged elements at cycles 21-23 is 53 $MW_{th}d/kgHM$ (heavy metal). Over many years of operation, MOX fuel elements have had about the same average burn-up at discharge of non-MOX elements. Although the above value does not reflect past conditions, it is slightly below the planned average burn-up of elements discharged in the future (52 - 55 $MW_{th}d/kgHM$ between 2003 and 2008). Therefore, the assumption of 53 $MW_{th}d/kgHM$ should approximately reflect average conditions over the lifetime of the plant.

MOX fuel elements will not be used for the last reactor cycles before shut-down, because their higher residual heat would require a residence time in cooling ponds higher than for spent fuel from fresh uranium. It is estimated that in 40 years lifetime all MOX fuel elements loaded in KKG will cover approximately 8% of the fuel requirements and corresponding total energy production. Currently, there is no reprocessed uranium in MOX for KKG. Part of the uranium from reprocessed spent fuel, with typically 0.5% to 0.6% of U-235, is stored and it will be re-enriched only if needed or if economically viable. Another part is shipped to Russia where it is blended with HEU to make RepU fuel elements.

In KKL no MOX fuel element is used yet. Hence all fuel is assumed to be from fresh uranium. The average enrichment of the discharged fuel elements at cycles 16-18 (year 2000-2002) is 3.8%, and the average burn-up 48.6 MWd/kgHM, according to the information received by the utility.[6] Reloads in recent years have had average enrichment of 4.1% and the prospective average burn-up at discharge may reach 55 MWd/kgHM.[7] However, considering that in past years the enrichment and burn-up were rather smaller (3.25% and 35 MWd/kgHM assumed for the 1996 edition of this study), and that the rated power has been increased by 18% from the first cycle, the average at discharge at cycles 16-18 appears to be an acceptable approximated average value to represent the lifetime of the plant.

Tab. 7.9 shows the values assumed in this study for average enrichment and burn-up for all modelled chains. For calculating fuel use in PWR & BWR UCTE, the CH, DE and FR values are weighted with their relative energy production.

Tab. 7.9 Key parameters for the modeled Swiss, French, German and UCTE LWRs.

Parameter		PWR				BWR		
		CH [a]	DE	FR	UCTE	CH	DE	UCTE
Average enrichment of fuel elements (fresh U)	%	4.2	4.0	3.8	3.9	3.8	4.0	4.0
Average burn-up	$MW_{th}d/kgU$	53	50	42.8	45	48.6	48	48
Net efficiency		0.32	0.33	0.33	0.33	0.32	0.33	0.33
Assumed fraction of MOX for lifetime		0.08	0.15	0.10	0.13	0.00	0.10	0.08
Specific fuel requirement	kgU/kWh	2.46E-06	2.53E-06	2.95E-06	2.81E-06	2.68E-06	2.63E-06	2.63E-06
Specific requirement of fresh fuel (incl. HEU)	kgU/kWh	2.26E-06	2.15E-06	2.66E-06	2.44E-06	2.68E-06	2.37E-06	2.42E-06

[a] The same values have been assumed for the cycle using exclusively centrifuge enrichment.

Tab. 7.10 shows the detailed radioactive emissions to air from the Swiss LWRs during 1995-2002, normalized by the net electricity production. The uncertainty interval for all measurements of the releases is declared to stay within ±50%. Values below 0.1% of the annual limit are not reported.

[6] Information by Mr. G. H. Devillaz and Ms. F. Geiger, NOK, 13 June 2003.

[7] Information by Dr. H. Bay, NOK, 23 May 2003.

Tab. 7.10 Radioactive emission species to air from the Swiss PWRs and BWRs. Averaged over 1995 – 2002 (BAG 1996-2003).

Isotope [kBq/kWh]	Beznau I & II	Gösgen	Leibstadt	Mühleberg	**PWR**	**BWR**	LWR
H-3			8.1E-02			**6.14E-02**	2.76E-02
C-14	2.7E-03	1.1E-02	5.3E-02	2.8E-02	**7.64E-03**	**4.67E-02**	2.52E-02
Ar-41				4.3E-03		**1.07E-03**	4.81E-04
Kr-85			8.0E-04	1.7E-02		**4.68E-03**	2.11E-03
Kr-85m	2.3E-02		9.5E-03	3.0E-02	**9.87E-03**	**1.47E-02**	1.20E-02
Kr-87			5.5E-03	7.1E-03		**5.94E-03**	2.67E-03
Kr-88			2.3E-03	2.5E-02		**7.86E-03**	3.54E-03
Kr-89				1.4E-02		**3.35E-03**	1.51E-03
Xe-131m				1.3E-01		**3.12E-02**	1.41E-02
Xe-133	3.8E-01	7.7E-01	4.4E-01	3.0E-01	**6.04E-01**	**4.07E-01**	5.15E-01
Xe-133m				4.3E-03		**1.07E-03**	4.81E-04
Xe-135	2.6E-01	9.5E-02	3.3E-01	2.4E-02	**1.66E-01**	**2.55E-01**	2.06E-01
Xe-135m			3.7E-01	4.9E-02		**2.89E-01**	1.30E-01
Xe-137			4.1E-05	3.7E-02		**9.17E-03**	4.13E-03
Xe-138			6.5E-02	8.0E-02		**6.83E-02**	3.08E-02
Other gases/nobles	3.9E-02	4.2E-01			**2.59E-01**		1.42E-01
Total gases					**1.05E+00**	**1.21E+00**	1.12E+00
I-131	4.0E-06	2.9E-06	8.2E-05	1.1E-05	**3.38E-06**	**6.44E-05**	3.09E-05
I-133	4.3E-06				**1.82E-06**		9.98E-07
Cr-51				1.2E-07		**2.89E-08**	1.30E-08
Mn-54			5.6E-09	4.3E-08		**1.48E-08**	6.66E-09
Co-58	3.9E-08		3.5E-09	7.1E-08	**1.64E-08**	**2.02E-08**	1.81E-08
Co-60	2.4E-08	1.1E-07	5.0E-08	9.1E-07	**7.57E-08**	**2.63E-07**	1.60E-07
Zn-65			9.1E-09	2.7E-07		**7.39E-08**	3.33E-08
Zr-95	1.4E-07		2.1E-09		**5.78E-08**	**1.59E-09**	3.25E-08
Nb-95		1.9E-10	2.2E-09		**1.12E-10**	**1.62E-09**	7.94E-10
Ru-103			5.1E-10			**3.86E-10**	1.74E-10
Ag-110m		5.4E-09			**3.13E-09**		1.72E-09
Cd-115m	6.4E-10				**2.70E-10**		1.48E-10
Sb-124		8.2E-10		8.7E-09	**4.75E-10**	**2.16E-09**	1.23E-09
Sb-125	5.6E-08				**2.34E-08**		1.28E-08
Cs-134			2.9E-08			**2.16E-08**	9.73E-09
Cs-137	1.7E-08	3.7E-10	9.8E-09	1.5E-06	**7.28E-09**	**3.74E-07**	1.73E-07
Ba-140		5.5E-10	2.2E-06	6.9E-07	**3.17E-10**	**1.86E-06**	8.39E-07
La-140			2.1E-07			**1.59E-07**	7.17E-08
Ce-141			6.0E-07	6.2E-09		**4.51E-07**	2.03E-07
Total beta aerosols	2.1E-07				**8.67E-08**		4.77E-08
Alpha aerosols	6.0E-09	4.9E-09	9.6E-09	6.0E-09	**5.37E-09**	**8.73E-09**	6.88E-09
Total aerosols					**5.47E-06**	**6.76E-05**	3.35E-05

Tab. 7.11 shows the detailed radioactive emissions to water from the Swiss LWRs during 1995-2002, normalized by the net electricity production. The class "mixed nuclides" includes all isotopes but tritium.

Tab. 7.11 Radioactive emission species to water from the Swiss PWRs and BWRs. Averaged over 1995 – 2002 (BAG 1996-2003).

Isotope [kBq/kWh]	Beznau I & II	Gösgen	Leibstadt	Mühleberg	**PWR**	**BWR**	LWR
H-3	2.00E+00	1.76E+00	9.11E-02	1.16E-01	**1.86E+00**	**9.75E-02**	1.08E+00
Na-24	2.38E-05	-	-	4.92E-06	**9.98E-06**	**1.25E-06**	6.13E-06
Cr-51	1.80E-05	-	4.50E-06	1.35E-03	**7.56E-06**	**3.45E-04**	1.56E-04
Mn-54	3.13E-05	-	1.19E-06	2.84E-04	**1.31E-05**	**7.29E-05**	3.94E-05
Fe-59	1.00E-06	-	2.30E-07	5.93E-07	**4.20E-07**	**3.22E-07**	3.77E-07
Co-57	2.13E-05	-	-	-	**8.92E-06**	**-**	4.99E-06
Co-58	2.72E-03	-	9.54E-07	3.06E-04	**1.14E-03**	**7.84E-05**	6.71E-04
Co-60	9.43E-04	3.67E-07	1.28E-05	3.29E-03	**3.95E-04**	**8.44E-04**	5.93E-04
Zn-65	6.27E-07	-	5.93E-06	7.01E-04	**2.63E-07**	**1.82E-04**	8.05E-05
Sr-89	8.71E-06	-	-	1.00E-04	**3.65E-06**	**2.55E-05**	1.33E-05
Sr-90/Y-90	3.11E-06	-	-	1.13E-05	**1.30E-06**	**2.87E-06**	1.99E-06
Zr-95	3.59E-06	-	-	1.10E-06	**1.50E-06**	**2.78E-07**	9.62E-07
Zr-97	5.20E-07	-	-	-	**2.18E-07**	**-**	1.22E-07
Nb-95	7.34E-06	-	1.20E-07	9.84E-06	**3.07E-06**	**2.59E-06**	2.86E-06
Mo-99	1.43E-08	-	-	6.98E-06	**6.00E-09**	**1.77E-06**	7.84E-07
Tc-99m	6.71E-06	-	-	1.47E-04	**2.81E-06**	**3.74E-05**	1.81E-05
Ru-103	6.81E-07	-	3.57E-08	-	**2.85E-07**	**2.67E-08**	1.71E-07
Cd-109	7.17E-06	-	-	-	**3.00E-06**	**-**	1.68E-06
Ag-110m	1.06E-05	-	2.22E-08	5.03E-03	**4.43E-06**	**1.28E-03**	5.65E-04
Sb-122	2.16E-06	4.39E-11	-	-	**9.04E-07**	**-**	5.05E-07
Sb-124	9.75E-05	8.83E-07	3.06E-08	3.85E-06	**4.13E-05**	**1.00E-06**	2.36E-05
Sb-125	9.93E-05	1.45E-07	5.10E-08	5.03E-06	**4.17E-05**	**1.31E-06**	2.39E-05
Te-123m	-	2.70E-06	-	-	**1.57E-06**	**-**	8.77E-07
Te-132	8.96E-08	8.03E-08	-	-	**8.42E-08**	**-**	4.71E-08
I-131	1.92E-05	3.15E-07	6.01E-06	5.41E-07	**8.21E-06**	**4.62E-06**	6.63E-06
I-133	9.93E-07	-	-	9.96E-06	**4.16E-07**	**2.53E-06**	1.35E-06
Cs-134	9.00E-06	-	8.27E-06	1.28E-07	**3.77E-06**	**6.21E-06**	4.84E-06
Cs-136	6.70E-07	-	-	-	**2.81E-07**	**-**	1.57E-07
Cs-137	2.39E-04	5.94E-09	1.35E-05	1.75E-03	**1.00E-04**	**4.53E-04**	2.56E-04
Ba-140	-	-	6.48E-06	-	**-**	**4.84E-06**	2.13E-06
La-140	1.18E-06	-	6.09E-06	-	**4.95E-07**	**4.55E-06**	2.28E-06
Ce-141	4.19E-07	-	2.31E-06	-	**1.76E-07**	**1.72E-06**	8.58E-07
Ce-144	1.15E-06	-	-	-	**4.82E-07**	**-**	2.69E-07
Alpha emitters	-	5.19E-08	6.28E-08	-	**3.02E-08**	**4.69E-08**	3.75E-08
Mixed nuclides	4.28E-03	4.55E-06	6.86E-05	1.30E-02	**1.79E-03**	**3.35E-03**	2.48E-03

The available detailed emission rates by isotopes (or classes) for the modelled French, German, and UCTE LWRs are provided in the German report. Here, only an overview of the average values for four classes of radioactive emissions to air and water is shown in Tab. 7.12. Remarkable differences can be seen for mixed nuclides to water between PWR-CH and BWR-CH, and between the Swiss and German or French plants. For the first comparison, the differences are determined by the composition of old and new units for the two types of power plants, where the old (and smaller) units emit two to three orders of magnitudes more (per unit of electricity). The mixed nuclides emissions from KKL are comparable with German BWRs, whereas mixed nuclides emissions from KKG are much lower than those from French and German plants. Prudence is recommended by using these numbers in different contexts.

Tab. 7.12 Summary of average radioactive emission classes to air and and water from the modelled PWR und BWR. Average 1995 – 2002 for Switzerland and 1995 – 1999 for UCTE countries.

		Net electricity production 1995-1999 (kWh)	Radioactive emissions (kBq/kWh)			
			Air		Water	
			Nobles + H3	Aerosols	Tritium	Mixed nuclides
PWR	CH	6.66E+10	1.05E+0	5.47E-6	1.86E+0	1.79E-3
	DE	5.44E+11	3.87E-1	7.01E-7	1.51E+0	2.11E-5
	FR	1.83E+12	9.16E-1	1.33E-5	1.85E+0	2.07E-4
	UCTE	2.89E+12	8.39E-1	9.78E-6	1.94E+0	3.60E-4
BWR	CH	5.25E+10	1.21E+0	6.76E-5	9.75E-2	3.35E-3
	DE	2.19E+11	3.69E-1	9.93E-6	2.45E-1	4.01E-5
	UCTE	3.27E+11	6.10E-1	2.24E-5	1.87E-1	5.85E-4

Radioactive solid wastes

Tab. 7.13 shows the radioactive waste production rates from the operation of KKG and KKL, normalized from the total amounts up to year 1992. Tab. 7.14 shows the solid wastes from the decommissioning of KKG from the relatively old study by the operators. These values have been conservatively (i.e. maximizing the waste production) used here, because the more recent assessement performed by the operators was not available. It is expected that they reduce by approximately one third.

Tab. 7.15 shows the waste rate production from decommissioning of KKG and KKL.

Tab. 7.13 Summary of the operational radioactive solid wastes for KKG and KKL.

From total produced till the end of 1992	KKG m^3/kWh	KKL m^3/kWh
to be conditioned in Zwilag	4.32E-11	4.68E-10
to Repository LLW, through Zwilag	1.76E-09	1.61E-08

Tab. 7.14 Solid wastes from the decommissioning of KKG (Nagra 1985b).

Waste mass				tonne
A.	Total mass to dispose of			325'765
B.	Non radioactive concrete and steel masses			185'830
C.	Wastes from the monitored area with activity below threshold			136'160
D.	Radioactive primary wastes (A-(B+C)) [c]			3'775
		low active	medium active	
D1 - Radioactive wastes		510	225	735
D2 - Contaminated wastes		1'410	1'630	3'040
E.	Secondary wastes			900
F.	Wastes to nuclear disposal (D+E)			4'675

Tab. 7.15 Radioactive wastes from the decommissioning of KKG and KKL to dispose of in the LLW repository.

	KKG	KKL
m^3	7'727	14'019
m^3/kWh	2.48E-8	4.05E-8

7.2.8 Reprocessing and conditioning of spent fuel

Two possible alternatives for the treatment of spent fuel have been described: reprocessing and conditioning by encapsulation of untreated spent fuel for direct disposal. The environmental inventories for reprocessing and conditioning are allocated to the spent fuel or heavy metal throughput. The differences between the mass of uranium in heavy metal and the total heavy metal are of the order of the percent. The waste products from reprocessing and the conditioned radioactive waste from the operation of power plants are transported to the Swiss Interim Storage.

Key data for reprocessing have been taken from the environmental report for the French facility in La Hague (Cogema 1998). Radioactive emissions data specific for the UK plant THORP in Sellafield have not been available. Data published on radioactive emissions from the entire site cannot be directly applied to the chain related to LWRs because they concern also reprocessing and further treatment of material unrelated to the operation of these reactor types.

Cogema's environmental report does not provide single radioactive isotopes emitted but a few classes. On the basis of previous data, C-14 releases could be extrapolated. The relatively high associated long term health effects were among the main findings of the assessment of the French nuclear chain performed for the ExternE project (Dreicer et al. 1995). They made a meaningful difference for the total health effects estimated for the facilities in La Hague and Sellafield, reflecting differences in the process. Additionally, emissions of single plutonium isotopes have been reconstructed from older references, because their absence may be negatively perceived.

The estimation of the various radioactive waste streams to return to the Swiss nuclear power plant operators has been made on the basis of the old project "Gewähr" on final repository (Nagra 1985a,b). As a matter of facts, at the time of the rework for this study, no design still existed for the repository for low and medium short-lived radioactive solid wastes, and the Nagra publications on the repository for high and medium long-lived radioactive wastes were not available when the input for the current modelling was worked out. Therefore, a decision was taken to maintain the coherent set developed for the previous versions of this study, with some adjustments, which can be seen as a conservative way to deal with the modeling because it ends up to maximize the volumes of the waste.

The present model for waste has been used unchanged also for the French, German, and the UCTE nuclear cycles. Therefore prudence shall be used to evaluate the corresponding results. Considering their relative importance, only the radioactive emissions to air and water during operation of La Hague as well as the waste streams associated with the spent fuel reprocessing are here summarized.

Table 1.17 and 1.18 give the available data on radioactive emission to air and water, respectively, from La Hague in 1996 and 1997, and the modifications introduced for the LCI dataset for reprocessing.

Tab. 7.16 Radioactive emissions to air from La Hague in 1996 and 1997 (Cogema 1998).

Radionuclides	1996		1997		1996	1997	**Assumed**
	Release (kBq/a)	Fraction of limit (%)	Release (kBq/a)	Fraction of limit (%)	(kBq/kgHM)	(kBq/kgHM)	(kBq/kgHM)
Tritium	7.47E+10	3.4	7.57E+10	3.44	4.44E+04	4.53E+04	**4.49E+04**
Halogens [a]	3.97E+07	36.1	1.82E+07	16.51	2.36E+01	1.09E+01	**1.73E+01**
Aerosols	2.00E+04	0.03	3.12E+04	0.04	1.19E-02	1.87E-02	**1.53E-02**
Others [b]	2.59E+14	53.96	2.97E+14	61.96	1.54E+08	1.78E+08	1.66E+08

a (Cogema 1998): Mostly I-129.

b (Cogema 1998): Mostly Kr-85 and C-14. On the basis basis of older references included in the 1996 edition of this study, this total has been split into **1.66E8 kBq/kgHM as nobles** and **1.66E4 kBq/kgHM as C-14**.

Tab. 7.17 Radioactive emissions to water from La Hague in 1996 and 1997 (Cogema 1998).

Radionuclides	1996 Release (kBq/a)	1996 Fraction of limit (%)	1997 Release (kBq/a)	1997 Fraction of limit (%)	1996 (kBq/kgHM)	1997 (kBq/kgHM)	**Assumed** (kBq/kgHM)
Tritium	1.05E+13	28.4	1.19E+13	32.2	6.25E+06	7.13E+06	**6.69E+06**
Total other radionuclides:	2.94E+10	1.7	3.90E+10	2.3	1.75E+04	2.34E+04	**2.04E+04**
Alpha emitters	4.60E+07	2.7	4.80E+07	2.8	2.74E+01	2.87E+01	**2.81E+01**
Cs-137 + Sr-90[a]	7.70E+09	3.5	4.32E+09	1.96	4.58E+03	2.59E+03	**3.58E+03**
Rest [b]	2.17E+10	k.A	3.46E+10	k.A	1.29E+04	2.07E+04	**1.68E+04**

a After references included in the 1996 edition of this study, the total has been split into **90% Cs-137** and **10% Sr-90**.
b Inventoried as „**Radioactive species, Nuclides, unspecified**“, assuming that all actinides are included in the alpha emitters.

Due to missing information on the most recent accounting of the volumes of the various classes of radioactive solid wastes from reprocessed spent fuel from Swiss nuclear reactors (project “Entsorgungsnachweis”), the volumes (including canisters) used in ecoinvent v1.1 are still based on the specifications used in the project “Gewähr” (Nagra 1985a, 1985b). Only key information are provided in the following. Tab. 7.18 shows the waste classes assumed in the project Gewähr. The specific volumes of the six waste classes are summarized in Tab. 7.19. The specific volumes of vitrified highly active wastes from the project Gewähr have been here recalculated based on the higher spent fuel burn-up, assuming same decay heat per unit of volume of the waste. The cylindrical steel container (approximately ∅ 940 mm and 2000 mm length) is included in the total volume. In the previous edition of this study the total volume included only the coquille (Tab. 7.19).

Tab. 7.18 Waste classes assumed in the project “Gewähr” (Nagra 1985b).

WA-1	Vitrified highly active waste in steel coquille
WA-2	Precipitations and concentrates in bitumen
WA-3	Ion exchange resins in cement
WA-4	End pieces and bushes in cement
WA-5	Low active alpha-contaminated technological waste in cement containers
WA-6	Medium active alpha-contaminated technological waste in cement containers

Tab. 7.19 Radioactive waste classes for reprocessed spent fuel from Swiss LWRs, after the project “Gewähr” (Nagra 1985b).

Repository LLW [m^3/kgHM]		Repository SF/H-ILW [m^3/kgHM]	
WA-3	1.11E-4	[WA-1 incl. coquille]	[2.20E-4]
WA-5	3.54E-3	WA-1 incl. canister	1.45E-3
		WA-2	5.42E-4
		WA-4	7.13E-4
		WA-6 [a]	1.77E-3
Total	3.65E-3	Total	4.47E-3

a In the project Gewähr and in the previous version of this study, WA-6 was assumed to be disposed of in the LLW repository.

7.2.9 Interim storage

The assessment of the Swiss interim storage plant (Zwilag) performed in the former editions of this study has not been updated, because from the point of view of inventory results this step contributes negligibly. However, the model was established when Zwilag was not yet built, while now it is operational, except for the incinerator. Therefore, part of the input values may not fully reflect the reality, although no meaningful changes in the inventory are expected. The approximation has been somewhat reflected in the uncertainties.

Of the three datasets representing the operation of the facility (see Fig. 7.1), two are functional for the different paths of the conditioned radwastes to the repositories (see below), and one describes the processing of low active wastes from the operation of the Swiss nuclear power plants, and includes the emissions to air from the incinerators and the emissions to water from cement conditioning.

Also for the interim storage the modelling has been made for the Swiss case only and used directly for the French, German, and UCTE nuclear cycles. Therefore, although it may not reflect the actual case in these countries, meaningful differences in the inventory are not expected.

7.2.10 Final repositories

The concept for the final geological repositories of radioactive wastes in Switzerland has changed. The old project "Gewähr" (Nagra 1985 a,b) with repository of highly radioactive waste in crystalline rock provided the data for the modelling in the previous editions of this study. The new project "Entsorgungsnachweis" (Nagra 2002 a,b) for the repository of spent fuel and reprocessed highly and intermediate long-lived radioactive wastes (SF/H-ILW) is based on the principle of partial reversibility (pilot plant on site) and deposition in opalinus clay strata. Therefore, major changes ought to be made to the dataset describing this repository. No information was available on a new design for the repository of low and medium short-lived radioactive wastes (LLW). Therefore, the old design was assumed still but with a different waste inventory along with information received from the responsible Swiss company Nagra. This is somehow reflected in the uncertainties. Main characteristics of these concepts are given in Tab. 12.3.

Tab. 7.20 Comparative characteristics of the old and new concepts for the final repository of radioactive wastes in Switzerland. The volumes include the canisters.

	Project Gewähr 1985	Project Entsorgungsnachweis 2002	This study
Reference scenario	240 GW·a	192 GW·a	192 GW·a
Repositories	2	2	2
SF		8'300 m^3	8'300 m^3
HLW		1'015 m^3	1'015 m^3
ILW		6'400 – 7'300 m^3	6'700 m^3
Total volume SF/H-ILW	11'100 m^3	15'700 – 16'600 m^3	16'000 m^3
Total volume LLW	200'000 m^3	~100'000 m^3	100'000 m^3

The basis scenario for the project "Entsorgungsnachweis" considered that approximately 40% (about 1200 tU) of the total spent fuel from the currently installed five Swiss LWRs after 40 years operation will be reprocessed. The assessment includes the amount of overburden, the material and energy uses for mining the tunnels, placing the wastes, and eventually sealing the repository. Details are not reported here because the contribution to cumulative inventories is relatively small due to the huge energy associated with the total waste (i.e., typical small volumes per unit of energy).

Long-term emissions

The risk studies performed by Nagra (e.g. (Nagra 2002a)) aim at demonstrating that the various man-made and natural passive barriers interposed between the conditioned radioactive wastes and the biosphere serve to delay the release of radioisotopes to the biosphere to $10^4 – 10^7$ years from the sealing of the repositories, and at estimating the maximum individual dosis to humans, which must remain below a threshold fixed by the Swiss Nuclear Authority at any time and for all possible release scenarios. The time when some isotopes might have a peak in the biosphere, but still much below the threshold (Nagra 2002a), is much greater than the time assumed in ecoinvent for the calculation of long-term releases from non-radioactive waste depositories (Doka 2003). Furthermore, it can be shown that even the amounts released over very long time remain very low when normalized to the electricity production corresponding to the total deposited waste. For all the above reasons, no release from the nuclear wastes in final repositories to the biosphere is accounted for in this LCI study. However, this important issue pertains risk assessment methodologies and studies, and the social implications of the final disposal of radioactive waste can be addressed together with all issues of interest in holistic multi-criteria evaluations (Hirschberg *et al.* 2003).

7.3 Cumulative Results and Analysis

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

7.3.1 Selected results

Tab. 7.21 through Tab. 7.23 show selected cumulative LCI results and cumulative energy demand for electricity production at the busbar of the modelled nuclear power plants and mixes. The discussion will be mostly on the BWR-CH and PWR-CH. No cumulative results for the other steps of the cycle will be presented. The reason is that intermediate products like enriched uranium or conditioned waste from reprocessing are practically pertaining the nuclear cycle only. Moreover, considering that with the only exception of the enrichment services (for which it was possible to define only approximate shares), no specific modeling for nuclear cycles associated with non Swiss LWR was performed. Therefore, a comparison of intermediate steps for the various chains is meaningless.

The breakdown for the discussion of some inventories is made for the following major steps: Mining, Milling, Conversion, Enrichment, Fuel fabrication, together making the Upstream part of the cycle; Power plant; and, Reprocessing, Conditioning, Interim storage, and Repositories LLW and SF/H-ILW, together making the waste management (or downstream) part of the cycle.

Tab. 7.21 Selected cumulative results and cumulative energy demand for electricity production at LWR mixes in Switzerland, Germany, and UCTE.

		Name		electricity, nuclear, at power plant	electricity, nuclear, at power plant	electricity, nuclear, at power plant
		Location		CH	DE	UCTE
		Unit	Unit	kWh	kWh	kWh
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.11E-01	1.36E-01	1.11E-01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.29E+01	1.15E+01	1.26E+01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	6.99E-03	4.19E-03	5.30E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.45E-04	7.17E-04	5.27E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.42E-02	1.30E-02	1.39E-02
LCI results						
resource	Land occupation	total	m2a	6.04E-03	5.53E-03	5.89E-03
		artificial surfaces	m2a	2.75E-04	2.67E-04	2.73E-04
air	Carbon dioxide, fossil	total	kg	7.81E-03	1.00E-02	7.72E-03
air	NMVOC	total	kg	8.10E-06	7.58E-06	8.30E-06
air	Nitrogen oxides	total	kg	3.97E-05	4.09E-05	4.01E-05
air	Sulphur dioxide	total	kg	3.97E-05	5.03E-05	3.71E-05
air	Particulates, < 2.5 um	total	kg	6.21E-06	6.36E-06	6.35E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	6.67E-06	6.51E-06	7.04E-06
air	Particulates, > 10 um	total	kg	1.61E-05	1.76E-05	1.58E-05
water	BOD	total	kg	1.40E-05	1.32E-05	1.52E-05
soil	Cadmium	total	kg	2.08E-11	1.90E-11	2.07E-11
Further LCI results						
resource	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	5.06E-06	4.87E-06	5.51E-06
resource	Iron, 46% in ore, 25% in crude ore, in ground	in ground	kg	2.96E-04	2.82E-04	3.16E-04
resource	Gravel, in ground	in ground	kg	3.60E-03	3.44E-03	3.80E-03
resource	Uranium, in ground	in ground	kg	2.30E-05	2.06E-05	2.24E-05
resource [radwaste]	Volume occupied, final repository for radioactive waste [BE/HAA/LMA]	in ground	m3	8.39E-09	8.18E-09	1.15E-08
resource [radwaste]	Volume occupied, final repository for low-active radioactive waste [SMA]	in ground	m3	4.71E-08	4.36E-08	4.50E-08
[radwaste]	[SAA]		m3	2.27E-08	2.09E-08	2.30E-08
[radwaste]	[Tailings]		m3	5.21E-06	4.67E-06	5.08E-06
air+water	Heat, waste	total	MJ	7.99E+00	7.50E+00	7.67E+00
air, radioactive	Radon (+Radium)	total	kBq	7.46E+02	6.69E+02	7.29E+02
air, radioactive	Edelgase	total	kBq	1.81E+02	1.72E+02	3.74E+02
air, radioactive	Aerosole	total	kBq	2.86E-04	2.12E-03	2.22E-04
air, radioactive	Aktinide	total	kBq	4.73E-04	4.22E-04	4.62E-04
water	Chloride	total	kg	9.74E-05	1.11E-04	9.78E-05
water	Cadmium, ion	total	kg	4.75E-09	4.48E-09	4.95E-09
water	Sulfate	total	kg	5.13E-04	4.68E-04	5.05E-04
water, radioactive	Radium	total	kBq	6.48E-02	5.80E-02	6.32E-02
water, radioactive	Tritium	total	kBq	8.37E+00	8.09E+00	1.68E+01
water, radioactive	Nuklidgemisch	total	kBq	2.47E-02	3.11E-01	4.62E-02
water, radioactive	Aktinide	total	kBq	2.11E-02	1.89E-02	2.07E-02

7.3.2 Analysis

Energy resource requirements

The total uranium ore consumption has been calculated for all analysed cycles in the interval $2.00 \cdot 10^{-5}$ kgU_{nat}/kWh to $2.39 \cdot 10^{-5}$ kgU_{nat}/kWh, depending upon the assumed burn-ups and average enrichment of fresh fuel. The greatest uranium requirements has been calculated for the French cycle, because the entirety of fresh fuel is assumed to be enriched in Tricastin, thus with relatively high electricity consumption of nuclear origin. The values for the mixes of PWR, BWR, and LWR for UCTE vary in the narrower range $2.24 \cdot 10^{-5}$ kgU_{nat}/kWh to $2.27 \cdot 10^{-5}$ kgU_{nat}/kWh.

Material requirements

The total material use can be estimated indirectly through the cumulative results for specific non-energy resources. As examples, the iron ore (representing steel and cast iron) and copper ore for metals as well as gravel as component of concrete are here discussed. As shown in Tab. 7.21 to Tab. 7.23, the differences for each item lie within 20%. This variation depends on the assumptions for fuel intensity (burn-up and associated uranium consumption), the material intensity for the construction of the power plant, and the extrapolation of infrastructure data from the Swiss to UCTE units. The greatest material use throughout the cycle is for the construction of power plants. Under the assumptions for this study, the intensity of gravel use for the PWR-CH chain is 15% lower than for BWR-CH, the total iron use 7% lower, whereas copper is slightly higher. The explanation is that while the higher amount of concrete and steel used for the construction of the BWR plant are not compensated by the assumed total higher electricity production from KKL compared to KKG, the absolute amount of copper has been assumed the same for both plants.

Tab. 7.22 Selected cumulative results and cumulative energy demand for electricity production at PWR in Switzerland, France, Germany, and UCTE.

		Name		electricity, nuclear, at power plant pressure water reactor	electricity, nuclear, at pressure water reactor, centrifugal enrichment	electricity, nuclear, at power plant pressure water reactor	electricity, nuclear, at power plant pressure water reactor	electricity, nuclear, at power plant pressure water reactor
		Location		CH	CH	DE	FR	UCTE
		Unit	Unit	kWh	kWh	kWh	kWh	kWh
LCIA results								
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	7.88E-02	7.82E-02	1.33E-01	9.00E-02	1.11E-01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.25E+01	1.23E+01	1.12E+01	1.34E+01	1.25E+01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	6.72E-03	6.88E-03	3.93E-03	5.42E-03	5.29E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.32E-04	3.66E-04	7.10E-04	3.02E-04	5.32E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.35E-02	1.32E-02	1.26E-02	1.46E-02	1.38E-02
LCI results								
resource	Land occupation	total	m2a	5.77E-03	5.64E-03	5.36E-03	6.20E-03	5.88E-03
		artificial surfaces	m2a	2.50E-04	2.45E-04	2.58E-04	2.80E-04	2.72E-04
air	Carbon dioxide, fossil	total	kg	5.19E-03	5.18E-03	9.80E-03	5.95E-03	7.74E-03
air	NMVOC	total	kg	7.73E-06	7.49E-06	7.40E-06	8.75E-06	8.33E-06
air	Nitrogen oxides	total	kg	3.39E-05	3.24E-05	3.99E-05	3.93E-05	4.04E-05
air	Sulphur dioxide	total	kg	2.25E-05	2.24E-05	4.89E-05	2.62E-05	3.71E-05
air	Particulates, < 2.5 um	total	kg	5.40E-06	5.20E-06	6.22E-06	6.26E-06	6.38E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	6.20E-06	6.08E-06	6.28E-06	7.43E-06	7.07E-06
air	Particulates, > 10 um	total	kg	1.29E-05	1.27E-05	1.71E-05	1.47E-05	1.58E-05
water	BOD	total	kg	1.35E-05	1.32E-05	1.29E-05	1.62E-05	1.53E-05
soil	Cadmium	total	kg	2.02E-11	1.97E-11	1.84E-11	2.21E-11	2.07E-11
Further LCI results								
resource	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	5.13E-06	5.02E-06	4.82E-06	5.97E-06	5.57E-06
resource	Iron, 46% in ore, 25% in crude ore, in ground	in ground	kg	2.86E-04	2.78E-04	2.73E-04	3.41E-04	3.17E-04
resource	Gravel, in ground	in ground	kg	3.35E-03	3.27E-03	3.29E-03	4.09E-03	3.80E-03
resource	Uranium, in ground	in ground	kg	2.24E-05	2.19E-05	2.00E-05	2.39E-05	2.24E-05
resource [radwaste]	Volume occupied, final repository for radioactive waste [BE/HAA/LMA]	in ground	m3	8.10E-09	7.83E-09	8.08E-09	1.37E-08	1.17E-08
resource [radwaste]	Volume occupied, final repository for low-active radioactive waste [SMA]	in ground	m3	3.49E-08	3.39E-08	3.56E-08	4.95E-08	4.25E-08
[radwaste]	[SAA]		m3	2.22E-08	2.25E-08	2.03E-08	2.44E-08	2.30E-08
[radwaste]	[Tailings]		m3	5.07E-06	4.96E-06	4.53E-06	5.42E-06	5.08E-06
air+water	Heat, waste	total	MJ	7.98E+00	7.76E+00	7.50E+00	7.82E+00	7.67E+00
air, radioactive	Radon (+Radium)	total	kBq	7.27E+02	7.12E+02	6.50E+02	7.76E+02	7.28E+02
air, radioactive	Edelgase	total	kBq	1.75E+02	1.65E+02	1.70E+02	5.09E+02	3.90E+02
air, radioactive	Aerosole	total	kBq	1.83E-04	1.79E-04	1.67E-04	2.31E-04	2.08E-04
air, radioactive	Aktinide	total	kBq	4.61E-04	4.47E-04	4.11E-04	4.95E-04	4.62E-04
water	Chloride	total	kg	7.74E-05	7.58E-05	1.11E-04	8.97E-05	9.89E-05
water	Cadmium, ion	total	kg	4.58E-09	4.51E-09	4.34E-09	5.24E-09	4.96E-09
water	Sulfate	total	kg	4.97E-04	4.87E-04	4.55E-04	5.31E-04	5.05E-04
water, radioactive	Radium	total	kBq	6.31E-02	6.17E-02	5.64E-02	6.74E-02	6.32E-02
water, radioactive	Tritium	total	kBq	8.92E+00	8.47E+00	8.38E+00	2.24E+01	1.77E+01
water, radioactive	Nuklidgemisch	total	kBq	2.32E-02	2.20E-02	2.11E-02	6.30E-02	4.83E-02
water, radioactive	Aktinide	total	kBq	2.05E-02	2.01E-02	1.84E-02	2.20E-02	2.07E-02

Waste heat

The total waste heat is prevalently (>95%) from the operation of the power plant. The way the waste heat has been inventoried is such that the difference between cumulative and direct output from a power plant may serve as a measure of the total energy uses throughout the cycle. Assuming a reference efficiency of conversion thermal energy to electricity of 35% to express the total energy requirements in electricity-equivalent units, the calculated range for these is between 0.011 kWh use per kWh produced at Swiss PWR in the hypothesis of centrifuge enrichment only up to 0.050 kWh use per kWh produced at French PWR. The average for current UCTE nuclear chains is 0.035 kWh use per kWh produced at LWRs.

Non radioactive air emissions

Total greenhouse gas (GHG) emissions in CO_2-equivalent for the time horizon of 100 years calculated after (IPCC 2001) are here discussed. Although it is not a pure inventory value, it allows a concentrated discussion of the emissions of the contributing species. In this respect, the single species of importance (CO_2, CH_4, N_2O, and the rest, which is made prevailently of CFCs and HCFCs) are also given separately in Fig. 7.2 and Fig. 7.3 for the modelled Swiss nuclear cycles. From Tab. 7.21 to Tab.

7.23 the range for the modelled European nuclear energy chains associated with LWRs is between 5 and 12 gCO_2-equiv./kWh. The cumulative values for LWR-Mixes variate in the narrower range 8 to 11 gCO_2-equiv./kWh. The differences can be attributed mostly to the share of enrichment by the USEC diffusion facility, supplied by coal power plants. Moreover, this plant is still authorized to refrigerate with CFC-114, but its specific emission is small compared to CO_2. The French diffusion enrichment plant contributes negligibly because it is supplied by nuclear power plants and cooled by water. The contribution from centrifuge enrichment to total GHG is very low due to its much lower energy intensity compared to diffusion. The GHG emissions from other steps are due to the use of fossil energy sources either directly or through the electricity mixes.

Tab. 7.23 Selected cumulative results and cumulative energy demand for electricity production at BWR in Switzerland, Germany, and UCTE.

		Name		electricity, nuclear, at power plant boiling water reactor	electricity, nuclear, at power plant boiling water reactor	electricity, nuclear, at power plant boiling water reactor
		Location		CH	DE	UCTE
		Unit	Unit	kWh	kWh	kWh
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.50E-01	1.44E-01	1.07E-01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.33E+01	1.23E+01	1.27E+01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	7.32E-03	4.84E-03	5.36E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.61E-04	7.36E-04	4.88E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.51E-02	1.42E-02	1.43E-02
LCI results						
resource	Land occupation	total	m2a	6.39E-03	5.96E-03	5.98E-03
		artificial surfaces	m2a	3.07E-04	2.90E-04	2.75E-04
air	Carbon dioxide, fossil	total	kg	1.10E-02	1.07E-02	7.45E-03
air	NMVOC	total	kg	8.52E-06	8.07E-06	8.13E-06
air	Nitrogen oxides	total	kg	4.70E-05	4.34E-05	3.90E-05
air	Sulphur dioxide	total	kg	6.09E-05	5.36E-05	3.60E-05
air	Particulates, < 2.5 um	total	kg	7.21E-06	6.70E-06	6.09E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	7.23E-06	7.09E-06	6.90E-06
air	Particulates, > 10 um	total	kg	2.01E-05	1.90E-05	1.57E-05
water	BOD	total	kg	1.47E-05	1.40E-05	1.45E-05
soil	Cadmium	total	kg	2.15E-11	2.03E-11	2.07E-11
Further LCI results						
resource	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	in ground	kg	4.97E-06	4.97E-06	5.00E-06
resource	Iron, 46% in ore, 25% in crude ore, in ground	in ground	kg	3.09E-04	3.04E-04	3.07E-04
resource	Gravel, in ground	in ground	kg	3.89E-03	3.79E-03	3.77E-03
resource	Uranium, in ground	in ground	kg	2.37E-05	2.20E-05	2.27E-05
resource [radwaste]	Volume occupied, final repository for radioactive waste [BE/HAA/LMA]	in ground	m3	8.75E-09	8.41E-09	9.08E-09
resource [radwaste]	Volume occupied, final repository for low-active radioactive waste [SMA]	in ground	m3	6.20E-08	6.32E-08	6.70E-08
[radwaste]	[SAA]		m3	2.32E-08	2.23E-08	2.26E-08
[radwaste]	[Tailings]		m3	5.37E-06	4.99E-06	5.14E-06
air+water	Heat, waste	total	MJ	8.02E+00	7.52E+00	7.67E+00
air, radioactive	Radon (+Radium)	total	kBq	7.70E+02	7.16E+02	7.36E+02
air, radioactive	Edelgase	total	kBq	1.88E+02	1.77E+02	2.21E+02
air, radioactive	Aerosole	total	kBq	4.11E-04	6.89E-03	3.47E-04
air, radioactive	Aktinide	total	kBq	4.89E-04	4.51E-04	4.67E-04
water	Chloride	total	kg	1.22E-04	1.12E-04	8.69E-05
water	Cadmium, ion	total	kg	4.97E-09	4.82E-09	4.86E-09
water	Sulfate	total	kg	5.32E-04	5.00E-04	5.09E-04
water, radioactive	Radium	total	kBq	6.68E-02	6.21E-02	6.39E-02
water, radioactive	Tritium	total	kBq	7.69E+00	7.40E+00	9.11E+00
water, radioactive	Nuklidgemisch	total	kBq	2.65E-02	1.02E+00	2.76E-02
water, radioactive	Aktinide	total	kBq	2.18E-02	2.02E-02	2.08E-02

CO_2 emissions make about 90% of the total for the cycles associated with the Swiss LWRs. The relatively high differences for the enrichment step for BWR-CH vs. PWR-CH is due to the assumption of 13% of BWR fuel enriched by USEC. Supply of all enriched uranium by USEC alone would raise the total for the enrichment step to approximately 55 gCO_2-equiv./kWh. CFC-114 makes only about 6% of the GHG emission from the USEC plant. The lowest GHG value is calculated for PWR-CH (assumption for enrichment services: 60% Eurodif, 40% Urenco) and in case PWR-CH would use centrifuge enrichment only. Therefore, this value can be assumed representative for near future nuclear cycles for LWRs. For the French cycle, assumed to use exclusively domestic enrichment services, about 6 gCO_2-equiv./kWh are calculated. Waste management gives only minor contribution to cumulative GHG. The power plant contributes slightly more than 1 gCO_2-equiv./kWh.

In general, direct as well as indirect emissions of NO_x, SO_x, and NMVOC from Milling are the greatest contributors to total, together with indirect contributions through the USEC enrichment services. Next contributions are from the power plant infrastructure and mining. The upstream produces more emissions of combustion products than the power plant and the back-end.

Radioactive air emissions

The cumulative radioactive emissions to air are summarized in the result tables. They have been aggregated in four categories to facilitate the discussion: Radon (including Rn-222 and Ra-226), Other gases and nobles (including all Kr and Xe isotopes, Ar-41 and the non-noble gases H-3 and C-14), Aerosols (including the isotopes of Ag, Ba, Ce, Co, Cr, Cs, Fe, I, La, Mn, Nb, Pb, Pm, Po, Ru, Sb, Sr, Tc, Te, Zn and Zr – plus K-40 from the coal chain), and Actinides (including all isotopes of U, Th, Pa, Pu, Am, Cm, and Np). No weighting factors have been attributed to single isotopes. Hence, the aggregated radioactivity cannot be directly used for calculation of health effects.

Fig. 7.4 and Fig. 7.5 show the radioactive air emissions from the cycles for PWR-CH and BWR-CH, respectively. The results are spanning over several orders of magnitude. At a first glance, the values for corresponding categories show practically no significant differences between the two cycles. The total actinides from the two chains exhibit only 6% difference. In terms of cumulative activity of actinides, mining and milling dominate with natural isotopes. Small amounts of actinides produced in the reactor may be released during reprocessing of spent fuel. However, the man-made actinides accounted for in input may not reflect the reality, because they might have been lumped in “Aerosols” in the environmental report of La Hague. Therefore, the results here shown for total actinides must be taken with prudence. Power plant and upstream of the PWR-CH and BWR-CH cycles have comparable emissions of aerosols. However, in the PWR cycle the upstream part gives higher emission, whereas in the BWR cycle it is the plant which emits somewhat more.

Radon is relased from mining and milling, and the predominant part is the long term emissions from mill tailings. Noble gases originate from power plant and reprocessing. The emission from reprocessing per unit mass of heavy metal is nearly three orders of magnitude higher than for the kgU in LWR fuel elements. The value shown in the tables for the Swiss cycles reflects the assumption of about 40% quota of spent fuel undergoing reprocessing. Emissions of nobles for other steps are indirect, prevailently through electricity requirements. In particular, the score for actinides, nobles, and radon is relatively high for enrichment due to the high supply share from the Eurodif plant.

The LWR and reprocessing are the major contributors to total release of radioactive aerosols. Typically, a BWR emits directly more aerosols than a PWR.

Non radioactive emissions to water

Sulfates are mostly released from mining (85% of total), corresponding to pyrite leaching from piles of mined material. Also chlorides are produced mostly from mining (55%). Of total cadmium emissions (exemplary for heavy metals) 40% are associated to mining, 20% to milling (mostly emitted directly in both cases), and about 25% to power plants (indirectly through material consumption).

Radioactive emissions to water

Liquid discharges from reprocessing are directly released into sea, whereas discharges from all other steps are assumed to be released into rivers. In Tab. 7.12 these emissions are summed up and given for four categories: Radium (including Ra isotopes); Tritium; Mixed nuclides (including isotope of Ag, Ba, C, Cd, Ce, Co, Cr, Cs, Fe, I, La, Mn, Mo, Na, Nb, Pb, Po, Ru, Sb, Sr, Tc, Te, Y, Zn and Zr — plus K-40 washed out from piles of coal ash); and ‘Actinides’ (including all isotopes of U, Th, Pa, Pu, Am, Cm, and Np). Again, no weighting factors have been considered for single isotopes.

Fig. 7.6 and Fig. 7.7 show the radioactive emissios to water from the upstream, power plant, and waste management parts of the cycles associated with PWR-CH and BWR-CH, respectively. The values of corresponding categories for the two cycles do not show major differences. However, differences can be seen for the power plant step, where the highest releases are depending on the corresponding direct emissions during operation: typically higher tritium release per kWh from the PWR-CH, and higher mixed nuclides release from the BWR-CH. Tritium und mixed nuclides in other steps originate from indirect sources only.

Naturally occurring radium is released basically from mining (97 %) and milling. The emissions of tritium und mixed nuclides originate prevalently from reprocessing (74% and 86%, respectively, for the PWR-CH cycle; 93% and 82%, respectively, for BWR-CH), in smaller amounts from the power plant (21% and 8%, respectively, for the PWR-CH cycle, 1% and 13%, respectively, for BWR-CH). The emissions of mixed nuclides for both reactors' cycles are one order of magnitude smaller than those from reprocessing (with only 40% of spent fuel treated there).

The direct emission of actinides can be divided into two parts, like for the corresponding air emissions: the natural isotopes, predominantly uranium und thorium from mining and milling, and man-made isotopes from reprocessing. All other contributions are indirect through electricity uses. In particular for the enrichment steps, all calculated emitted species derive from the PWR electricity supply to the Eurodif facility.

Radioactive solid waste

Fig. 7.8 shows the volumes per kWh of the four categories of radioactive solid wastes from the PWR-CH and BWR-CH cycles. BWRs produce typically more LLW from operation and decommissioning (44% of total from the cycle) than PWRs. Also the H-ILW volume is higher by 7%, due to the slightly higher mass of spent fuel per kWh. The higher LAW (4%) and uranium mill tailings (5%) are due to the slightly higher fuel requirement and the lack of MOX in BWR-CH, which implies higher requirement of fresh uranium per kWh compared to PWR-CH.[8]

The estimated SF/H-ILW and LLW production rates should be taken with caution. As explained above, the volumes of HLW assumed in this study do not consider the reduction the reprocessing industry is pursuing. Moreover, they do not consider that the total volume of radioactive waste from decommissioning of the power plant has been reestimated lower than assumed in the 1980s. Besides, the volume of uranium mill tailings is an guesstimate of the world average, which may not reflect averages for specific national policies. Furthermore, values for annual or total radioactive solid volumes that could be calculated using the rates given above should not be applied directly to conditions different from the ones modelled in this study for Switzerland, i.e. two geological final repositories, a certain spectrum of waste types for the SF/H-ILW repository, share of reprocessed vs. non-reprocessed spent fuel, and use of MOX.

[8] The total volumes estimated in ecoinvent v1.01 are different than those in the previous edition of the study. For example, PWR-CH now has: +76% volume SF/H-ILW, due to a correction to include the steel canister and the consideration of one more class of conditioned waste from reprocessing, once destined to the LLW repository; -29% volume LLW for the previously mentioned reason; -26% volume LAW; and approximately -15% volume tailings due to the different modelling of the cycle.

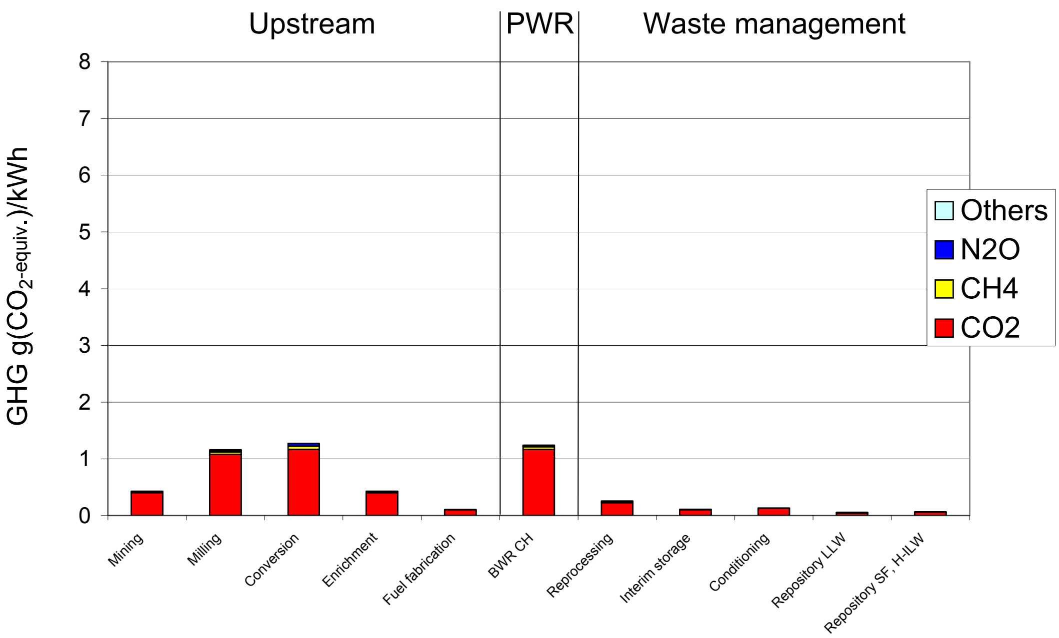

Fig. 7.2 **Contributions of single species to total GHG emission in CO_2-equivalent per kWh from single steps of the modelled nuclear fuel cycle for the PWR-CH.**

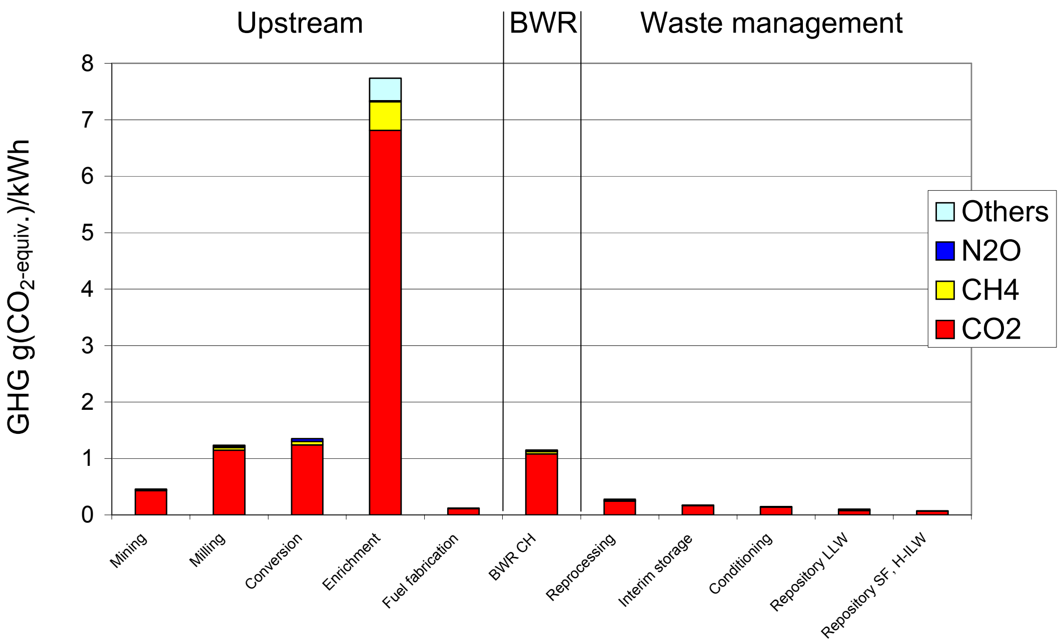

Fig. 7.3 **Contributions of single species to total GHG emission in CO_2-equivalent per kWh from single steps of the modelled nuclear fuel cycle for the BWR-CH.**

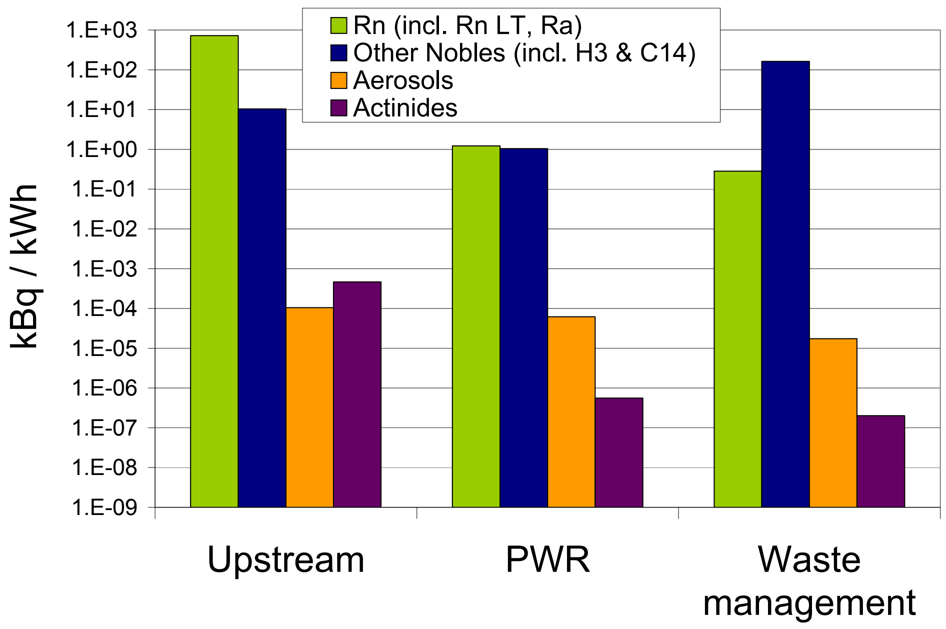

Fig. 7.4 Radioactive emissions to air from the upstream, power plant, and waste management parts per kWh of the modelled nuclear fuel cycle for the PWR-CH.

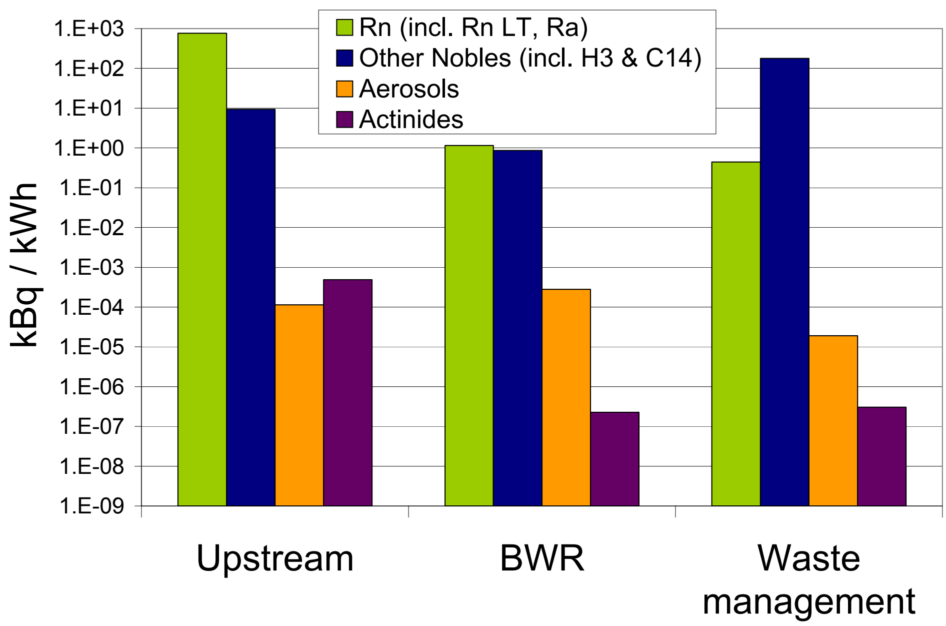

Fig. 7.5 Radioactive emissions to air from the upstream, power plant, and waste management parts per kWh of the modelled nuclear fuel cycle for the BWR-CH.

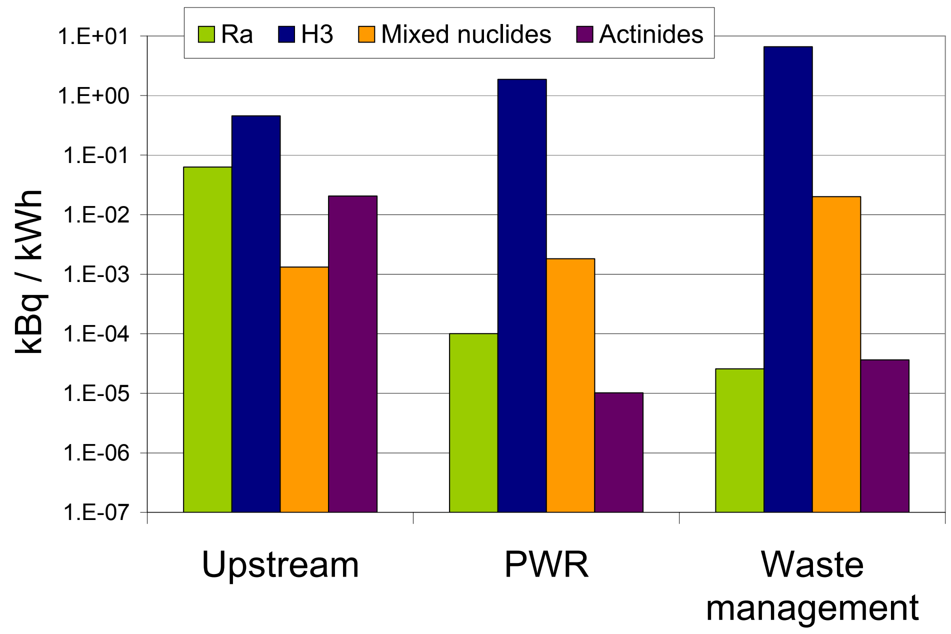

Fig. 7.6 **Radioactive emissions to water from the upstream, power plant, and waste management parts per kWh of the modelled nuclear fuel cycle for the PWR-CH.**

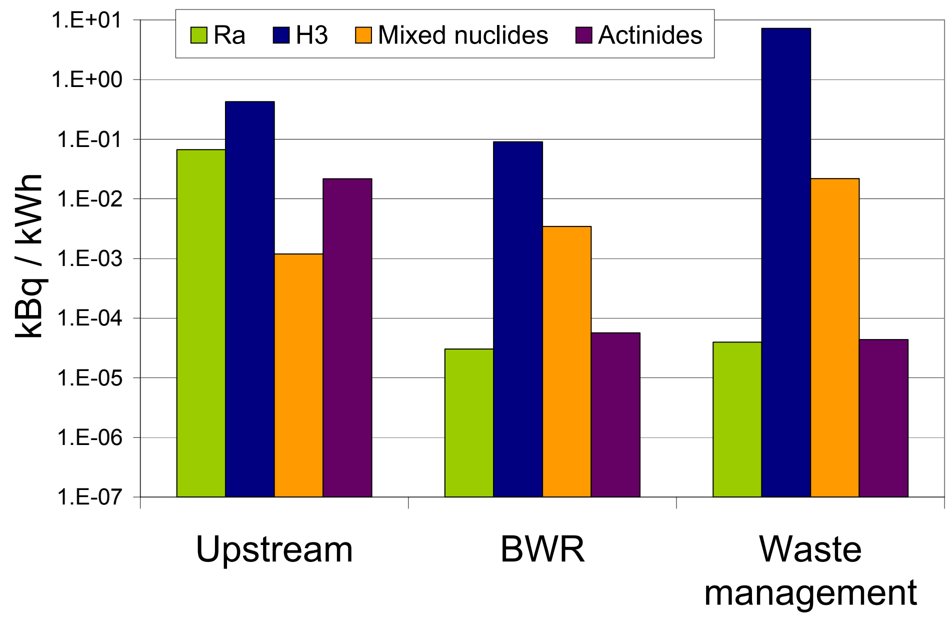

Fig. 7.7 **Radioactive emissions to water from the upstream, power plant, and waste management parts per kWh of the modelled nuclear fuel cycle for the BWR-CH.**

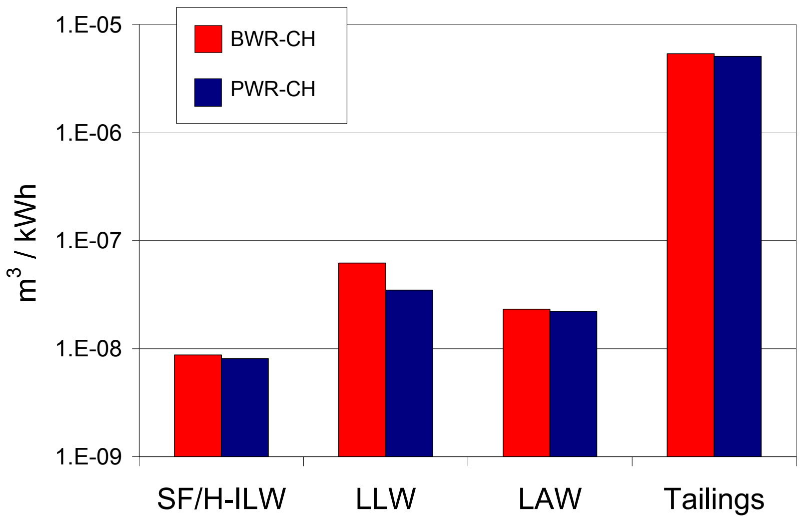

Fig. 7.8 Radioactive solid wastes per kWh from the modelled BWR-CH and PWR-CH nuclear fuel cycles.

7.4 Conclusions and outlook

It is recommended not to use the power plant datasets and the cumulative inventory results for comparisons of country-specific LWRs or LWR types and associated cycles. This is because several inventoried species depend upon the assumptions made for the enrichment services, whose shares rapidly change with the years, and allocation for different streams of fissile material. Results for non-Swiss conditions should not be used for comparing national nuclear cycles with each other. Instead, ecoinvent results provide meaningful intervals for the environmental burdens from nuclear power in Western Europe. In case specific issues on different strategies for the nuclear fuel cycle or location-specific characteristics would be in focus, sensitivity analyses or new studies should be performed. In particular, consideration of reactor types different from LWRs or different nuclear cycles or different fissile materials would definitively require the performance of appropriate LCA case studies.

The model for Swiss conditions for waste management has been extrapolated to other UCTE countries. This may not reflect different conditions, although substantial changes in the cumulative inventory results for the cycle are not expected from this source, with the exception of radioactive emissions from reprocessing.

The main subjects not or partially addressed in this study which may have some influence in the cumulative results for the cycle are summarized in the following:

Mining: chemical extraction; reclamation phase for conventional mines.

Milling: long-term (>100 years) emissions from tailing ponds into groundwater.

Fuel elements: MOX manufacturing plants.

Power plant (LWR): infrastructure of the 1300 MW class; reestimation of contaminated waste from decommissioning.

Reprocessing: current waste production rate per unit mass of heavy metal; detailed information on isotopic species released during operation; radioactive wastes from decommissioning.

Waste management: country-specific approaches for final repository; shallow land depository of low level radwaste.

7.5 References

BAG 1996-2003	Bundesamt für Gesundheit (BAG) (1996-2003) Umweltradioaktivität und Strahlendosen in der Schweiz. BAG, Abteilung Strahlenschutz, Sektion Überwachung der Radioaktivität. Freiburg, Schweiz.
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, Dübendorf, CH. Bezug unter: www.ecoinvent.ch.
Dreesen et al. 1982	Dreesen D.R. et al., (1982) Preliminary Evaluation of Uranium Mill Tailings Conditioning as an Alternative Remedial Action Technology. In: *Proc. NEA Workshop Uranium Mill Tailings Management*. Colorado State University, OECD, Paris.
Dreicer et al. 1995	Dreicer M., Tort V., und Manen P. (1995) Nuclear Fuel Cycle - Estimation of Physical Impacts and Monetary Valuation for Priority Pathways. Report Nº 234 prepared for DG XII of CEC in the framework of the ExternE Project. CEPN, Fontenay aux Roses, France.
EPA 1983	Office of Radiation Programs of US Environmental Protection Agency (1983) Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192), Volume I. EPA 520/1-83-008-1, USEPA, Washington D.C., USA.
Frischknecht et al. 2003a	Frischknecht R., Jungbluth N. (Eds), Althaus H.-J., Doka G., Dones R., Hellweg S., Hischier R., Nemecek T., Rebitzer G., Spielmann M. (2003) Overview and Methodology – Data v1.01 - ecoinvent Report No.1. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland.
IPCC 2001	Intergovernmental Panel on Climate Change (IPCC) (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, (Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Mohrhauer 1995	Mohrhauer H. (1995) Entwicklung bei der Uran-Anreicherung. atw **40** 8/9.
Nagra 2002a	Nagra (2002a) Projekt Opalinuston - Konzept für die Anlage und den Betrieb eines geologischen Tiefenlagers. Entsorgungsnachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Technischer Bericht 02-02. Nationale Genossenschaft für die Lagerung radioaktiverAbfälle (Nagra), Wettingen, Schweiz.
Nagra 2002b	Nagra (2002b) Project Opalinus Clay - Safety Report. Demonstration of disposal feasibility for spent fuel, vitrified high level waste and long-lived intermediate-level waste (Entsorgungsnachweis). Technical Report 02-05. Nationale Genossenschaft für die Lagerung radioaktiverAbfälle (Nagra), Wettingen, Switzerland.
Nagra 1985a	Nagra (1985) Nukleare Entsorgung Schweiz, Konzept und Übersicht über das Projekt Gewähr 1985. NGB 85-01. Baden, Schweiz.
Nagra 1985b	Nagra (1985) Radioaktive Abfälle: Eigenschaften und Zuteilung auf die Endlager-Typen. NGB 85-02. Baden, Schweiz.
NEA 1984	Nuclear Energy Agency - Organisation for Economic Co-operation and Development (NEA-OECD) (1984) Long-term radiological aspects of management of wastes from uranium mining and milling. OECD, Paris, Frankreich.

Paducah 1982	Paducah Gaseous Diffusion Plant (1982) Final Environmental Impact Assessment of the Paducah Gaseous Diffusion Plant Site. DOE/EA-0155 (DE83001211). Paducah, Kentucky, USA.
Senes 1998	Senes Consultants Limited (1998) Long-Term Population Dose due to Radon (Rn-222) Released From Uranium Mill Tailings. Prepared for The Uranium Institute. Senes Consultants Limited, Richmond Hill, Ontario, Canada.
Trowbridge 1991	Trowbridge L.D. (1991) Enrichment Technical Operations - Greenhouse Warming Potential of Candidate Gaseous Diffusion Plant Coolants. Prepared by the Uranium Enrichment Organization, managed by Martin-Marietta Energy Systems, Inc. for the U.S. Department of Energy, contract DE-AC05-84OR2140.
UI 1995	Tim Meadley (1995) Uranium Institute, Persönliche Mitteilung, London, UK.
UMTSP 1986	Uranium Mill Tailings Study Panel - Board on Radioactive Waste Management - Commission on Physical Sciences, Mathematics, and Resources - National Research Council (1986) Scientific Basis for Risk Assessment and Management of Uranium Mill Tailings. National Academy Press, Washington D.C., USA.
Urenco 2000	Urenco (2000) Urananreicherungsanlage Gronau – Umwelterklärung 1999. Urenco Deutschland GmbH, Gronau, Deutschland.
Van der Stricht & Janssens 2001	Van der Stricht S., Janssens A. (2001) Radioactive effluents from nuclear power stations and nuclear fuel reprocessing plants in the European Union, 1995-1999. Radiation Protection, 127. European Commission, Directorate-General Environment. Office for Official Publications of the European Communities, Luxembourg.

8 Hydro Power

Authors: Christian Bauer & Rita Bolliger, PSI

8.1 Modelled hydropower systems

Although electricity production at hydropower plants does not produce any direct air emissions except greenhouse gases, hydropower is not free of environmental burdens. Relatively large amounts of energy and materials are required, with associated environmental burdens, during construction of the plants. Main goal of this study is the quantification of these burdens for Swiss conditions and extrapolation to European hydropower plants in order to estimate their contributions to country-specific electricity mixes.

8.1.1 Reservoir hydropower plants

Electricity production at reservoir hydropower plants is modelled on the basis of data from more than 50 Swiss reservoir power plants. Only concrete dams with a height of more than 30 metres are taken into account. The dams analysed for this study correspond to 9130 MW installed capacity with an expected electricity production of 17.9 TWh/a and account for about 75% of total electricity production by Swiss reservoir power plants. The range of rated power is between 0.5 MW and 1200 MW. Average requirements are calculated by weighting the plant-specific values by the electricity production.

A dataset for electricity production at an average reservoir power plant in Switzerland is generated with these data. Plant-specific energy and material requirements as well as volume of reservoirs and size of flooded area are weighted by plant-specific electricity production. Some of the surveyed power plants include pumped storage plants, but these were not separated for the calculation of the average reservoir.

Datasets for electricity production at reservoir power plants in other regions – Europe, alpine conditions and non-alpine conditions, and Finland – are same as for Swiss dams with the exception of electricity mix for electricity supply, greenhouse gas emissions (see section 8.2.7), and size of flooded area. Due to lack of resources for a detailed analysis, this extrapolation is mainly addressed by increasing the uncertainty factors of the Swiss inventories. Therefore, results of these extrapolations cannot be considered definitive; rather, they should be seen as a basis for future more detailed studies.

Tab. 8.1 shows an overview of the datasets available in the ecoinvent database for electricity production at reservoir power plants.

Tab. 8.1 Ecoinvent datasets for electricity production at reservoir hydropower plants

Name	Location	Unit
electricity, hydropower, at reservoir power plant	CH	kWh
electricity, hydropower, at reservoir power plant	FI	kWh
electricity, hydropower, at reservoir power plant, alpine region	RER	kWh
electricity, hydropower, at reservoir power plant, non alpine regions	RER	kWh

8.1.2 Run-of-river hydropower plants

The average Swiss run-of-river hydropower plant is modelled on the basis of data from four Swiss and one Austrian run-of-river plants; the data are weighted by the specific electricity production. The range of rated power is between 23 MW and 237 MW.

The dataset for average European electricity production at run-of-river power plant is the same as for the average Swiss plant. Due to lack of resources for a detailed analysis, the extrapolation is mainly addressed by increasing the uncertainty factors of the inventoried Swiss data. Therefore, the results for non-Swiss plants cannot be considered definitive; rather, they should be seen as a basis for later more detailed studies. Tab. 8.2 shows an overview of the datasets available in the ecoinvent database for electricity production at run-of-river power plants.

Tab. 8.2 Ecoinvent datasets for electricity production at run-of-river hydropower plants

Name	Location	Unit
electricity, hydropower, at run-of-river power plant	CH	kWh
electricity, hydropower, at run-of-river power plant	RER	kWh

8.1.3 Country-specific hydro-mix

In order to represent hydropower in country-specific electricity production, country-specific electricity generation at hydropower plant is modelled for single UCTE, CENTREL, and NORDEL countries as well as for Ireland and Great Britain. Country-specific shares of electricity production at reservoir and run-of-river power plants in year 2000 are used for this modelling. Alpine conditions for reservoir plants are assumed for Austria, Italy, and France, non alpine for all other countries. Tab. 8.3 shows hydroelectricity production data in European countries in year 2000. In the ecoinvent database, one dataset is available for each contry to represent the relevant hydropower mix. Name of each dataset is “electricity, hydropower, at power plant”, complemented by the proper location identifier.

Tab. 8.3 Electricity production [GWh] and shares of run-of-river and reservoir hydropower plants in year 2000 (Frischknecht & Faist Emmenegger 2003)

Country	**Production** [GWh]		**Share** [%]	
	Run-of-river	Reservoir	Run-of-river	Reservoir
Switzerland	17566	19448	46	54
Belgium	454	0	100	0
Germany	19398	3434	85	15
Spain	19153	9835	66	34
France	55666	10603	84	16
Greece	3656	0	100	0
Italy	15635	28031	36	64
Slovenia	3771	0	100	0
Croatia	877	4416	2	98
Bosnia-Herzegovina	3403	1833	65*	35*
Serbia and Montenegro	9423	1977	84	16
Macedonia	193	884	18	82
Luxembourg	119	0	100	0
Netherlands	141	0	100	0
Austria	30211	10517	75	25
Portugal	7511	3699	66	34
Czech Republic	1305	435	75**	25**
Hungary	176	0	100	0
Poland	2084	0	100	0
Slovak Republic	3509	1170	75**	25**
Denmark	30	0	100	0
Finnland	3613	10840	25	75
Norway	0	140181	0***	100***
Sweden	62276	15569	80	20
Great Britain	5086	0	100	0
Ireland	838	0	100	0

* Assumed same shares as in former Yugoslavia in early 1990’s.

** Assumed same shares as in Austria.

*** Own assumption.

8.1.4 Pumped storage hydropower plants

Electricity production at pumped storage power plants is modelled separately for each country with a hydro-mix. Infrastructure data and its requirement per kWh are assumed the same as for reservoir plants, since it is impossible to separate requirements for the construction of reservoir and pumped storage power plants within the available data for Swiss reservoirs. The difference among the modelled datasets for operation is the electricity used for pumping, which is in general assumed to be supplied by the country-specific high voltage grid. Common name for these datasets is "electricity, hydropower, at pumped storage power plant", complemented by the proper location identifier.

8.2 System description

8.2.1 System boundaries

Fig. 8.1 gives a schematic overview of the modelled electricity production chain for both reservoir and run-of-river power plants.

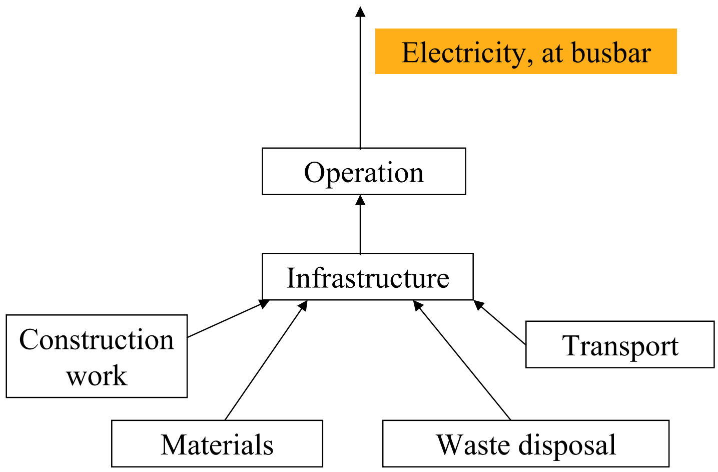

Fig. 8.1 Schematic overview of the modelled hydropower chain.

The infrastructure includes: material requirements for the construction of the plants; the disposal assumed at end of life; transport of construction materials; and, construction work (energy requirements and particle emissions). Lubricating oil is needed during operation of the plants. Greenhouse gases emitted during operation of reservoir hydropower plants are also taken into account.

8.2.2 Material requirements

Cement, gravel, steel, and water are included as construction materials. The cement use is assumed to be 230 kg/m^3 concrete for reservoir and 285 kg/m^3 concrete for run-of-river power plants. The relative shares of cement/gravel/water to make concrete are assumed to be 1/8.5/0.5 in first approximation. Concrete is required for the dams of both reservoir and run-of-river power plants, for lining of tunnels, and for buildings. Steel is required as reinforcement for the dams, for lining of tunnels, for turbines, generators, etc. Within this study, 25% of total steel requirements are assumed to be reinforcing steel (which accounts for all uses of unalloyed steel), 15% chromium steel, and 60% low-alloyed steel.

8.2.3 Construction

Construction of hydropower plants requires energy in form of electricity for various applications and diesel for building machines. Explosives are used for blasting of tunnels and ground preparation. Particle emissions from excavation, blasting, and concrete mixing are taken into account. Since there are no data available for particle emissions due to excavation during construction of hydropower plants, data on amounts related to limestone and bauxite mining (Kellenberger et al. 2005 „Building products“, Althaus et al. 2005 “Metals”) are used as first approximation for the construction of reservoirs. Size distribution of particle emissions is assumed to be the same as for limestone mining (Kellenberger et al. 2005) for both reservoirs and run-of-river plants. In case of construction of run-of-river plants it can be expected that particle emissions per unit of removed material are smaller, because of the higher share of humid soil. The amounts of particle emission due to excavation are also based on limestone and bauxite mining, as well as on plant specific information from the site “Wildegg-Brugg” (NOK 1956). Particle emissions originating from concrete mixing are based on information from (EPA 2002), using emission data for controlled batching.

8.2.4 Transport

Only transports of materials on public roads and railway tracks to the construction site are taken into account. Energy requirements for transports within the construction site by lorries and cablecars are included in total energy requirements for construction work. Transport distances are highly dependent on the location. Gravel is usually extracted near to or even at the construction site. Therefore, cement, steel and explosives are the only materials transported over long distances. Data used within this study originate from data referring to the hydropower plants at Bergell (Bertschinger 1959).

8.2.5 Waste treatment and disposal

Hydropower plants built in the middle of the last century have not reached the end of their lifetime. Therefore, there is no experience of disposal of concrete dams. This study assumes that the power plants are dismantled and dams remain on site. For this reason, the entire mass of cement, gravel, and reinforcing steel is accounted for as “disposal, building, reinforced concrete, to final disposal” as first approximation. This dataset includes energy requirements for demolition with building machines, which might not reflect actual cases. However, there is no information and experience concerning this disposal available. Steel used for tunnels and shafts probably remains on place as well. This fact, as well as disposal of steel used for machines, is taken into account with the input “disposal, steel, 0% water, to inert material landfill”. Used lubricating oil is burned in hazardous waste incineration plants.

8.2.6 Lifetime and Electricity production

Lifetime and expected annual electricity production are two key factors for the calculation of specific environmental burdens. Tab. 8.4 shows the assumed lifetimes for different parts of reservoir and run-of-river power plants.

The expected electricity production over the whole lifetime of one actual plant depends on the capacity as well as the climatological and hydrological conditions of that plant. In this study, all normalized values (per kWh electricity at busbar) for material, energy, and transport requirements as well as emissions from construction and operation of the mix of plants are determined as average of the available data for single plants weighted by the specific expected annual electricity production. The calculated electricity production of 2.56×10^{12} kWh for the average unit representing the Swiss mix of reservoir power plants and 1.24×10^{12} kWh for the the average unit representing the Swiss mix of run-of-river power plants is just a normative number in order to input all data per unit of infrastructure (i.e., the average plant). Therefore, these numbers should not be used for any single hydropower plant.

Tab. 8.4 Assumed lifetimes of different parts of reservoir and run-of-river hydropower plants, used for this study

	Reservoir power plants [1] [a]	Run-of-river power plants [2] [a]
Cement in dams	150	80
Cement in tunnels, control units	100	80
Reinforcing steel	150	80
Steel for turbines and tubes	80	40

[1] Personal communication from Walter Hauenstein, Director of Schweizer Wasserwirtschaftsverband, June 2002.
[2] Personal communication from Hansjürg Vögtlin, Colenco Power Engineering AG, June 2002, concerning construction of run-of-river power plant Ruppoldingen 1996-2000.

8.2.7 Greenhouse gas emission

Due to the anaerobic degradation of flooded biomass and composition of flooded soil in reservoirs, emissions of CO_2, CH_4, and N_2O can occur. In general, greenhouse gas emissions are increasing with decreasing depth of reservoirs and increasing temperatures. Using the limited information available on Swiss natural lakes, the following values have been chosen for this study: 0.014 g/kWh for CH_4 and $7.7 \cdot 10^{-5}$ g/kWh for N_2O, both also assumed for general alpine conditions. From the literature, 30 g CO_2-Äquiv./kWh are assumed for Finland, and 6 g CO_2-Äquiv./kWh for non alpine conditions.[9]

However, a full analysis considering net greenhouse gas emissions including the entire catchment area and pre and after impoundment conditions could not be performed, as specific research is still at beginning in Canada, Finnland, and Brazil.

8.2.8 Land use

The areas assumed for land use for Swiss average hydropower reservoirs are: “Transformation, to water bodies, artificial” $2.28 \cdot 10^{-5}$ m^2/kWh for the reservoir, and “Transformation, to industrial area, built up” $2.3 \cdot 10^{-7}$ m^2/kWh for the dam. The relevant land occupation for the reservoir is calculated using the lifetime in Tab. 8.4. Same input is used for European reservoirs with alpine conditions (Austria, Italy, and France). Due to a different topography with smaller mountains, it is assumed that reservoir lakes are shallower in Finnland and in European non-alpine countries. Therefore, land occupation and transformation are increased by a factor of 10.

Average run-of-river power plants are expected to be similar for different countries in Europe. Therefore, land use is estimated to be the same as assumed for Switzerland, namely $5.57 \cdot 10^{-5}$ m^2/kWh for “Transformation, to water courses, artificial” and $5.63 \cdot 10^{-7}$ m^2/kWh for “Transformation, to industrial area, built up” for the dam and power house.

8.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

8.3.1 Selected results

Tab. 8.5 and Tab. 8.6 show selected cumulative LCI results and cumulative energy demand for electricity production at the busbar of the modelled reservoir and run-of-river power plants, respectively. Selected results for all further modelled datasets can be found in the German report (Bolliger & Bauer 2004).

[9] Values for greenhouse gas emissions are based on information from (Van de Vate & Gagnon 1997), (Svensson 1999), (Gagnon & Varfalfvy 2000), and (Vattenfall 2002).

Country-specific results for average electricity production at hydropower plant mixes can be easily derived using the reservoir to run-of-river shares in Tab. 8.3. Country-specific results for electricity production at pumped storage power plants are directly dependent on the country-specific electricity mix assumed for pumping. No selected results are shown here for mixes and pumped storage, but the interested reader can either find them in the German report or directly retrieve them from the database.

Tab. 8.5 Selected cumulative results and cumulative energy demand for electricity production at modelled reservoir power plants (CH; FI; Europe, alpine conditions; Europe, non alpine conditions)

		Name		electricity, hydropower, at reservoir power plant	electricity, hydropower, at reservoir power plant	electricity, hydropower, at reservoir power plant, alpine region	electricity, hydropower, at reservoir power plant, non alpine regions
		Location		CH	FI	RER	RER
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	3.08E-02	3.59E-02	3.59E-02	3.59E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.13E-02	1.01E-02	1.01E-02	1.01E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.62E+00	4.62E+00	4.62E+00	4.62E+00
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.10E-04	2.12E-04	2.12E-04	2.12E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.52E-04	2.00E-04	2.00E-04	2.00E-04
LCI results							
resource	Land occupation	total	m2a	3.69E-03	3.52E-02	3.70E-03	3.52E-02
air	Carbon dioxide, fossil	total	kg	3.67E-03	4.06E-03	4.06E-03	4.06E-03
air	NMVOC	total	kg	3.98E-06	4.06E-06	4.06E-06	4.06E-06
air	Nitrogen oxides	total	kg	2.62E-05	2.70E-05	2.70E-05	2.70E-05
air	Sulphur dioxide	total	kg	4.30E-06	6.17E-06	6.17E-06	6.17E-06
air	Particulates, < 2.5 um	total	kg	1.20E-05	1.21E-05	1.21E-05	1.21E-05
water	BOD	total	kg	6.89E-06	7.18E-06	7.18E-06	7.18E-06
soil	Cadmium	total	kg	2.35E-12	2.43E-12	2.43E-12	2.43E-12
Further LCI results							
air	Dinitrogen monoxide	total	kg	1.85E-07	1.17E-07	1.94E-07	1.17E-07
air	Methane, biogenic	total	kg	1.40E-05	4.50E-09	1.40E-05	4.50E-09
air	Carbon dioxide, biogenic	total	kg	4.98E-05	3.01E-02	5.39E-05	6.05E-03
air	Particulates, > 2.5 um, and < 10um	total	kg	5.53E-05	5.54E-05	5.54E-05	5.54E-05
air	Particulates, > 10 um	total	kg	7.28E-05	7.31E-05	7.31E-05	7.31E-05

Tab. 8.6 Selected cumulative results and cumulative energy demand for electricity production at modelled run-of-river power plants (CH; Europe)

		Name		electricity, hydropower, at run-of-river power plant	electricity, hydropower, at run-of-river power plant
		Location		CH	RER
		Unit	Unit	kWh	kWh
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	2.85E-02	3.08E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	7.07E-03	6.48E-03
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.39E+00	4.39E+00
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	9.03E-05	1.36E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.05E-04	1.26E-04
LCI results					
resource	Land occupation	total	m2a	4.64E-03	4.64E-03
air	Carbon dioxide, fossil	total	kg	2.88E-03	3.05E-03
air	NMVOC	total	kg	4.61E-06	4.63E-06
air	Nitrogen oxides	total	kg	3.15E-05	3.18E-05
air	Sulphur dioxide	total	kg	3.98E-06	4.82E-06
air	Particulates, < 2.5 um	total	kg	1.76E-05	1.77E-05
water	BOD	total	kg	8.19E-06	8.31E-06
soil	Cadmium	total	kg	2.03E-12	2.07E-12
Further LCI results					
air	Dinitrogen monoxide	total	kg	5.05E-08	5.41E-08
air	Methane, biogenic	total	kg	3.99E-09	2.94E-09
air	Carbon dioxide, biogenic	total	kg	3.26E-05	3.44E-05
air	Particulates, > 2.5 um, and < 10um	total	kg	9.03E-05	9.03E-05
air	Particulates, > 10 um	total	kg	1.10E-04	1.10E-04

8.3.2 Analysis

A comparison between selected results for electricity production at reservoir power plants and electricity production at run-of-river power plants shows only relatively small differences for most elementary flows. Only greenhouse gas emissions, as shown in Fig. 8.2, can be higher for electricity production at reservoir power plants, depending on the direct emissions from reservoirs assumed to occur during operation. The emission breakdown in Fig. 8.2 is performed on the basis of the scheme in Fig. 8.1. Differences of cumulative results for other environmental flows within each category reservoir / run-of-river power plants for the various regions are small, which is a consequence of the assumption that most of the elementary flows are the same for all modelled regions. These results should not be considered as representative for single power plants in any of these regions.

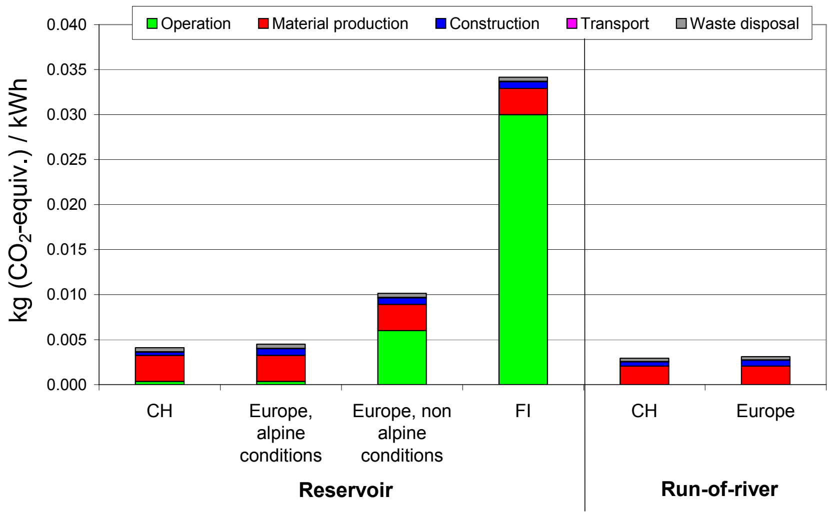

Fig. 8.2 **Greenhouse gas emissions from electricity production at reservoir power plants (CH; Europe, alpine and non-alpine conditions; FI) and run-of-river power plants (CH; Europe), originating in different sectors (GWP 100 a from IPCC 2001)**

In general, cement and steel requirements as well as diesel and electricity requirements for the construction of the plant are responsible for most of the cumulative results. Only in a few cases, like cadmium released to soil, transport requirements may give a high contribution to total, though the specific emissions are relatively small. In this case, cadmium originates from tyre abrasion. The cumulative emission of particles are dominated by direct emission during construction, wich include conrete mixing, and cement production. However, it has to be stressed that due to lack of specific data the particle emissions during construction are taken from bauxite mining and therefore affected by high uncertainty. The emission of $PM_{2.5}$ is shown in Fig. 8.3 for Swiss datasets, where the breakdown is again referring to the scheme in Fig. 8.1.

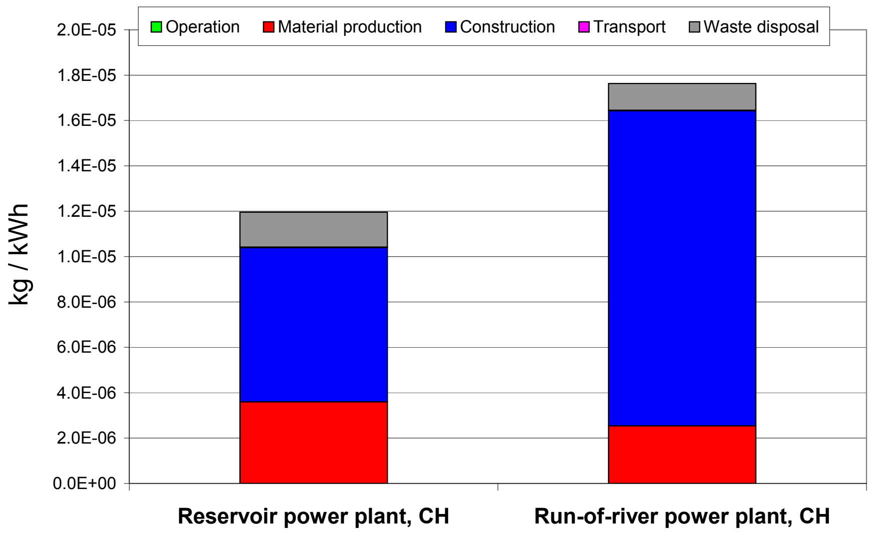

Fig. 8.3 Particle emissions (<2.5 μm) from electricity production at Swiss reservoir and run-of-river power plants, originating in different sectors

In case of cumulative energy demand and particle emissions, the assumed demolition of dams is relatively important. However, dams remaining standing on site after shutdown of the power plant may be considered as a realistic alternative instead of full demolition. Therefore, the burdens estimated here from the assumed demolition of dams should be considered only as a hint to take into account the post-operational phase of the lifetime.

Differences in electricity supply – Swiss supply mix for Switzerland and UCTE-mix for European datasets – are reflected in the shares of fossil and nuclear energy resources to cumulative energy demand for reservoir and run-of-river plants (see Tab. 8.5 and Tab. 8.6), but in general they do not cause major differences in total results. Conversely, the country-specific electricity mix used for pumping energy in pumped storage determines dramatic differences in the cumulative results.

8.4 Conclusions and outlook

The cumulative results of this study can be regarded as highly representative for electricity production at Swiss reservoir power plants. However, the results shall not be used to describe single reservoirs, because site-specific topographical and hydrological conditions and hence material and energy intensity as well as direct emissions might greatly differ from plant to plant. The results for average electricity production at run-of-river power plants in Switzerland can also be regarded as representative, in spite of the more limited data available.

Results for hydropower in other European countries cannot be considered ultimate for country-specific conditions, rather only as first approximation to serve the assessment of electricity mixes. Major divergence may occur especially for plants in countries with hydrological and topographical conditions very different from alpine regions. Therefore, further LCA studies are recommended in case country-specific assessments would be used for purposes different from the one in this study.

All final results are normalized to the kWh electricity available at the busbar. Therefore, they are highly dependent on the expected annual energy production and the assumed lifetime. Since there is no meaningful experience on concrete dams approximating their end of life and no information is available but for Swiss conditions, assumed relevant inputs might be regarded as relatively uncertain.

An important factor, which might need to be reworked, is the net emission of greenhouse gases from reservoirs. These emissions are highly affected by plant specific conditions like temperature, amount and type of flooded biomass, depth of reservoir, and type of soil. Only little information was available on this topic, and a full investigation was out of scope for this study. However, this should not be an issue of major concern for electricity production at reservoir power plants in Switzerland and other alpine regions, as temperatures are low and only relatively little amounts of biomass are flooded. Anyway, greenhouse gas emissions assumed for reservoir power plants in this study might not reflect plant specific conditions, especially for non-alpine regions. Further studies concerning this topic would be desireable for these regions.

Although the data on Swiss hydropower plants are relatively complete, more detailed information on the share of steel types, the type of energy and transport requirements during construction, as well as time factors differentiated for various contributions would be preferable.

Biological and hydrological effects of hydropower plants as well as possible effects on society (e.g. for relocation), which could not be reduced into LCA factors, are not included in this study. These factors must be addressed in plant-specific environmental impact assessments.

8.5 References

Althaus et al. 2004 — Althaus H.-J., Blaser S., Classen M. and Jungbluth N. (2004) Life Cycle Inventories of Metals. Final report ecoinvent 2000 No. 10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.ch.

Bertschinger 1959 — Bertschinger H. (1959) Versorgungs- und Transportprobleme beim Bau der Bergeller Kraftwerke der Stadt Zürich. In: Wasser- und Energiewirtschaft, 51(7), pp. 191-198.

Bolliger & Bauer 2004 — Bolliger R. and Bauer C. (2004) Wasserkraft. 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 & Faist Emmenegger 2003 — Frischknecht R. and Faist Emmenegger M. (2003) Strommix und Stromnetz. 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.

Gagnon & Varfalfvy 2000 — Gagnon L. and Varfalfvy L. (2000) Greenhouse Gas Emissions from Boreal Reservoirs, Quebec, Canada.

IPCC 2001 — IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (ed. Houghton J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Svensson 1999 — Svensson B. (1999) Greenhouse gas emissions from hydroelectric reservoirs - the need of a new appraisal. SwedPower AB, University of Kalmar, Sweden.

Van de Vate & Gagnon 1997 — Van de Vate J.F., and Gagnon L. (1997) Greenhouse gas emissions from hydropower – The state of research in 1996. In: *Energy Policy, Vol. 25, No. 1, pp. 7-13.*

Vattenfall 2002 — Vattenfall (2002) Sammanfattning av Vattenfall Abs Certifierade Miljövarudeklaration av El fran Lule/Ume älv. Information available at: http://www.environdec.com/swe/epdforteckning.asp.

9 Wood Energy

Author: Christian Bauer, PSI

9.1 Introduction

Sustainable use of wood is one alternative to the use of fossil fuels for heat production, in order to contribute to the reduction of greenhouse gas emissions, since carbon contained in the burned wood and hence emitted as CO_2 was taken from the atmosphere during the growth of the trees.

In year 2000, about 2.3 million m^3 of wood were used as fuel in Switzerland, generating 19970 TJ energy, which covered about 2.3% of total energy demand (BfE 2001). The sustainable potential of wood in Switzerland for fuels is estimated between 5.5 Mm^3 and 7 Mm^3 (BfS/BUWAL 2000).

The main goal of this study is the quantification of environmental burdens associated with wood boilers and wood cogeneration in Switzerland. Only boilers and cogeneration units are described in this report, whereas the upstream chain has been adressed by Werner et al. (2003). However, cumulative results include the full energy chain, along with all energy systems.

9.2 Modelled heating systems

The conventional wood furnaces and boilers addressed are listed in Tab. 9.1. Only wood directly from forests or untreated residual wood from the wood industry is used as firewood. Due to possible contamination, combustion of waste wood or chemically treated residual wood would require special emission control. Hardwood (beech), softwood (spruce), and the Swiss commercial mix of both types (28% and 72%, respectively) are considered. The wood as fuel is available as log, chip, or pellet. Industrial residual wood is used for pellet production.

Tab. 9.1 Conventional wood heating systems: ecoinvent datasets

<table>
<tr><th>Type</th><th>Fuel</th><th>Dataset</th></tr>
<tr><td rowspan="9">Wood logs heating</td><td rowspan="3">hardwood</td><td>heat, hardwood logs, at furnace 100kW</td></tr>
<tr><td>heat, hardwood logs, at furnace 30kW</td></tr>
<tr><td>heat, hardwood logs, at wood heater 6kW</td></tr>
<tr><td rowspan="3">softwood</td><td>heat, softwood logs, at furnace 100kW</td></tr>
<tr><td>heat, softwood logs, at furnace 30kW</td></tr>
<tr><td>heat, softwood logs, at wood heater 6kW</td></tr>
<tr><td rowspan="3">mixed</td><td>heat, mixed logs, at furnace 100kW</td></tr>
<tr><td>heat, mixed logs, at furnace 30kW</td></tr>
<tr><td>heat, mixed logs, at wood heater 6kW</td></tr>
<tr><td rowspan="18">Wood chips heating</td><td rowspan="6">hardwood</td><td>heat, hardwood chips from forest, at furnace 1000kW</td></tr>
<tr><td>heat, softwood chips from forest, at furnace 300kW</td></tr>
<tr><td>heat, hardwood chips from forest, at furnace 50kW</td></tr>
<tr><td>heat, hardwood chips from industry, at furnace 1000kW</td></tr>
<tr><td>heat, softwood chips from industry, at furnace 300kW</td></tr>
<tr><td>heat, hardwood chips from industry, at furnace 50kW</td></tr>
<tr><td rowspan="6">softwood</td><td>heat, softwood chips from forest, at furnace 1000kW</td></tr>
<tr><td>heat, hardwood chips from forest, at furnace 300kW</td></tr>
<tr><td>heat, softwood chips from forest, at furnace 50kW</td></tr>
<tr><td>heat, softwood chips from industry, at furnace 1000kW</td></tr>
<tr><td>heat, hardwood chips from industry, at furnace 300kW</td></tr>
<tr><td>heat, softwood chips from industry, at furnace 50kW</td></tr>
<tr><td rowspan="6">mixed</td><td>heat, mixed chips from forest, at furnace 1000kW</td></tr>
<tr><td>heat, mixed chips from forest, at furnace 300kW</td></tr>
<tr><td>heat, mixed chips from forest, at furnace 50kW</td></tr>
<tr><td>heat, mixed chips from industry, at furnace 1000kW</td></tr>
<tr><td>heat, mixed chips from industry, at furnace 300kW</td></tr>
<tr><td>heat, mixed chips from industry, at furnace 50kW</td></tr>
<tr><td rowspan="2">Pellets heating</td><td rowspan="2">pellets</td><td>heat, wood pellets, at furnace 15kW</td></tr>
<tr><td>heat, wood pellets, at furnace 50kW</td></tr>
</table>

Tab. 9.2 shows an overview of key parameters for the modelled heating systems. The given efficiencies (η_a) include thermal losses during the combustion, losses due to shutdown and startup of the boilers, and in case of the 30 kW and 100 kW log boilers also the thermal losses of the hot water storage tank. Losses of the heat distribution to heating elements are not accounted for.

Tab. 9.2 Key data of the modelled heating systems

Type	Capacity	Operation time	Energy output	η_a	Energy input	Fuel	Wood requirement		Lifetime of boiler
	[kW]	[h/a]	[MJ/a]	[%]	[MJ/a]		[t_{dry}/a]	[m^3/a]	[a]
Pellets heating	15	2100	113 400	82	138 293	pellets	7.3	11.1	15
	50	2100	378 000	85	444 705	pellets	23.5	35.7	15
Wood log heating	6	1000	21 600	75	28 800	hardwood	1.57	2.4	20
						softwood	1.51	3.4	20
						mixed	1.52	3.1	20
	30	1600	172 800	68	230 400	hardwood	13.8	21.3	15
						softwood	13.3	29.5	15
						mixed	13.4	27.2	15
	100	1600	576 000	70	738 462	hardwood	45.0	69.3	15
						softwood	43.1	95.7	15
						mixed	43.5	88.3	15
Wood chips heating	50	2100	378 000	80	472 500	hardwood	25.5	107	20
						softwood	24.7	146	20
						mixed	25.0	133	20
	300	2100	2 268 000	82	2 765 854	hardwood	151	631	20
						softwood	145	858	20
						mixed	146	774	20
	1000	2100	7 560 000	85	8 894 118	hardwood	486	2031	20
						softwood	466	2759	20
						mixed	471	2496	20

9.3 Modelled cogeneration plants

Two cogeneration plants installed in Switzerland have been modelled, each with two different pollution control units. Mixed industrial wood chips are used as fuel. Tab. 9.3 shows an overview of the datasets. Each set has been recalculated for three different allocation schemes: exergy, energy, and heat. The cogen 6400 kW unit uses a steam cycle, whereas the 1400 kW plant uses an Organic Rankine Cycle. Tab. 9.4 gives an overview of key parameters of the wood cogen plants.

Tab. 9.3 Datasets for wood cogeneration

Type	Emission control	Dataset
Cogen 6400 kW	Multi-Cyclone	heat, at cogen 6400kWth, wood, allocation energy /exergy /heat
		electricity, at cogen 6400kWth, wood, allocation energy /exergy /heat
	Baghouse filter, SNCR	heat, at cogen 6400kWth, wood, emission control, allocation energy /exergy /heat
		electricity, at cogen 6400kWth, wood, emission control, allocation energy /exergy /heat
Cogen 1400 kW	Multi-Cyclone	heat, at cogen ORC 1400kWth, wood, allocation energy /exergy /heat
		electricity, at cogen ORC 1400kWth, wood, allocation energy /exergy /heat
	Baghouse filter, SNCR	heat, at cogen ORC 1400kWth, wood, emission control, allocation energy /exergy /heat
		electricity, at cogen ORC 1400kWth, wood, emission control, allocation energy /exergy /heat

Tab. 9.4 Key data of the modelled wood cogeneration plants

		Cogen 1400 kW		Cogen 6400 kW	
		Multi-Cyclone	Emission control	Multi-Cyclone	Emission control
Wood requirement	t_{dry}/a	2231		3227	
	m³/a *	11829		17110	
Energy input	MJ/a	4.22E+7		6.10E+7	
Electric capacity	kW_{el}	335	306	400	386
Thermal capacity	kW_{th}	1440	1440	6400	6400
Net electricity production	kWh/a	3.72E+5	3.40E+5	1.40E+6	1.35E+6
Net heat production	MJ/a	3.24E+7	3.24E+7	4.68E+7	4.68E+7
Total efficiency	%	77.7	77.6	79.0	78.9

* Bulk density for dry wood.

9.4 System description

9.4.1 System boundaries

Fig. 9.1 shows a simplified description of the wood chain for heat production at conventional heating systems and combined heat and electricity production at cogeneration plants.

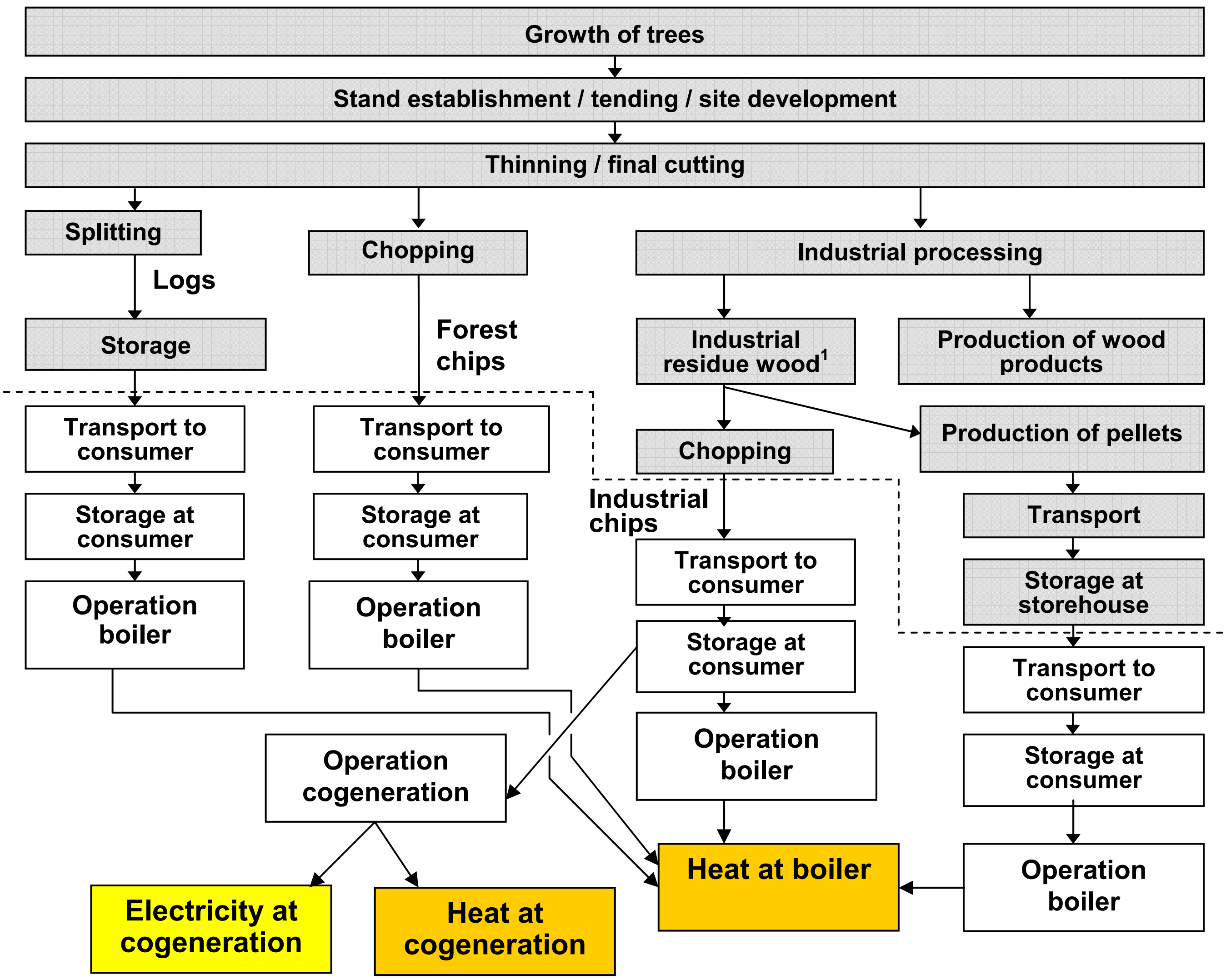

Fig. 9.1 Wood energy chain for heat production at conventional heating systems and combined heat and electricity production at cogeneration plants. Processes modelled in (Werner et al. 2003) are above the dotted line.

Detailed information about the upstream processes is available in (Werner et al. 2003). Industrial chips are produced from residues of the wood industry. Environmental burdens from wood processing are practically almost entirely allocated to wood products because of the economic criteria used in (Werner et al. 2003). Therefore, the upstream chain gives relatively small contributions to total burdens in case of industrial chips, as will be illustrated below.

9.4.2 Wood fuels

Wood chips from forest and industry (softwood, hardwood, mixed), wood logs (softwood, hardwood, mixed), and wood pellets are used as fuels for the modelled wood heating systems. Mixed industrial wood chips from industry are burned at wood cogeneration plants. Tab. 9.5 gives an overview of key data of the wood fuels, as defined in (Werner et al. 2003).

Tab. 9.5 Key data of wood fuels, after (Werner et al. 2003)

Fuel	Type of wood	Water content u [%]	Density incl. water [kg/m^3]	Bulk density, dry [kg/m^3]	LHV, wet [MJ/kg]	LHV, dry [MJ/kg$_{dry}$]
Forest chips, at forest	hardwood	80	1170	239	9.4	18.3
	softwood	140	1080	169	7.4	19.1
	mixed	120	1113	189	7.9	18.9
Industrial chips, at plant	hardwood	40	910	239	12.6	18.3
	softwood	40	630	169	13.4	19.1
	mixed	40	708	189	13.1	18.9
Logs, 2 years storage	hardwood	20	780	650	15.0	18.3
	softwood	20	540	450	15.7	19.1
	mixed	20	607	506	15.5	18.9
Pellets, at storehouse	mixed	10	1200	660	16.7	18.9

9.4.3 Transport of wood fuels to consumers

Transport distances of wood fuels between production and combustion sites are dependent on local conditions and may differ with type of heating system. The assumed average transport distances and vehicles for different heating systems installed in Switzerland are given in Tab. 9.6.

Tab. 9.6 Transport distances and transport vehicles for wood fuels burned at different heating systems

Heating system	Capacity [kW]	Transport distance [km]	Transport vehicle
Log heating	6	10	Tractor + trailer
	30	10	Tractor + trailer
	100	10	Tractor + trailer
Chips heating	50	20	Lorry 16 t
	300	20	Lorry 16 t
	1000	30	Lorry 16 t
Pellets heating	15	100	Lorry 16 t
	50	100	Lorry 16 t
Cogeneration	6400	50	Lorry 16 t
	1400	50	Lorry 16 t

9.4.4 Boiler infrastructure

Data for material and energy requirements for the production of wood boilers are based on information from one manufacturing company in Switzerland.[10] Since this company does not produce a wide spectrum of boilers, some extrapolations were necessary to describe all defined datasets. Only the most important materials of the boilers are included in the inventory: steel (as low alloyed steel), concrete, rock wool, ceramic tiles, polyurethane, and lubricating oil. The materials for wood chips and pellets boilers also include concrete for the storage room of the chips or pellets.

The infrastrucure of the cogeneration plants is divided into three parts: a suitable building, included in the inventory because the modelled cogeneration units are relatively large; components for heat and electricity generation; components for electricity generation only. The modelled 30 kW and 100 kW log boilers need a hot water storage tank. As the infrastructure of the modelled heating and cogeneration systems has no significant influence on the final cumulative results for the heat and electricity produced, the data on materials are not further discussed here.

All construction materials are transported to the boiler manufacturing company assuming the ecoinvent standard distances for Switzerand. Additionally, the conventional boilers are assumed to be transported 100 km by lorry 16 t and the cogeneration units 200 km by 28 t lorry and 200 km by train to the final location of installation.

The following disposal routes are assumed for the materials used in wood boilers and cogeneration devices: plastics are burned at municipial waste incinerators; rock wool and concrete are assumed to be delivered to inert material landfill; used lubricants are disposed of in hazardous waste incineration; reinforced concrete and gravel used for the building are disposed of in a sorting plant; all other materials are recycled.

9.4.5 Boiler operation

Wood log boilers are usually manually fed at time intervals of 4 to 6 hours. Wood chip and pellet boilers are fed automatically by a conveyor screw. These boilers have an automatic combustion control for the regulation of excess air and temperature, which is usually between 800°C and 1300°C. Therefore, the combustion of wood logs is less homogenous than the combustion of pellets and chips..

Energy requirements

Modern wood boilers may need some electricity for operation. Here it is assumed that chip and pellet boilers require electricity equivalent to 1.5% fuel energy, 30 kW and 100 kW log boilers require 1%, whereas the 6 kW log furnace works without electricity.[a]

Emissions

Emission data for the different modelled wood heating systems are based on measurements available in the literature for test facilities and actually installed boilers. In case of main emission species – particles, NO_x, and CO – plenty of information is available. On the other hand, the values used for other substances – CH_4, NMVOC, N_2O, and SO_x, and trace elements – are based on a few measurements reported in the literature. Combustion conditions at test facilities are ideal and the used fuel is homogenous. Hence, emissions of particles, NO_x, CO, CH_4, and NMVOC per unit of energy are smaller than considering the whole heating period (which includes start-up and shut-down). The differences depend on the capacity of the boilers and the installation of an automatic combustion control. Therefore, emission data from test facilities have been increased by multiplicative correction factors between 1.05 and 1.5, in order to reflect realistic operational conditions and match the measurements taken at actually installed boilers (Tab. 9.7). Also the start-up and shut-down phases are

[10] Personal communication from Mr. Hasler, Tiba AG, Bubendorf, June 2001.

taken into account using emission factors between 1 and 1.5, depending on the capacity and used fuels (Tab. 9.8).[11] The two sets are then multiplied in order to get the final correction factors.

Tab. 9.7 Correction factors for measurements at test facilities, considering not ideal combustion conditions and inhomogenous fuels during operation of actually installed boilers.

	NO_x	Particles	CO	CH_4	NMVOC	VOC	SO_2	N_2O	Others
Log boiler 6 kW	1.10	1.50	1.50	1.50	1.50	1.50	1	1	1
Pellets heating 15 kW	1.10	1.10	1.10	1.10	1.10	1.10	1	1	1
Log boiler 30 kW	1.10	1.50	1.50	1.50	1.50	1.50	1	1	1
Pellets heating 50 kW	1.05	1.10	1.10	1.10	1.10	1.10	1	1	1
Chips heating 50 kW	1.05	1.10	1.10	1.10	1.10	1.10	1	1	1
Log boiler 100 kW	1.10	1.50	1.50	1.50	1.50	1.50	1	1	1
Chips heating 300 kW	1.05	1.10	1.10	1.10	1.10	1.10	1	1	1
Chips heating 1000 kW	1.05	1.10	1.10	1.10	1.10	1.10	1	1	1

Tab. 9.8 Correction factors for measurements at test facilities, considering start-up and shut-down phases.

	NO_x	Particles	CO	CH_4	NMVOC	VOC	SO_2	N_2O	Others
Log boiler 6 kW	1	1.50	1.50	1.50	1.50	1.50	1	1	1
Pellets heating 15 kW	1	1.20	1.20	1.20	1.20	1.20	1	1	1
Log boiler 30 kW	1	1.35	1.35	1.35	1.35	1.35	1	1	1
Pellets heating 50 kW	1	1.10	1.10	1.10	1.10	1.10	1	1	1
Chips heating 50 kW	1	1.10	1.10	1.10	1.10	1.10	1	1	1
Log boiler 100 kW	1	1.20	1.20	1.20	1.20	1.20	1	1	1
Chips heating 300 kW	1	1	1	1	1	1	1	1	1
Chips heating 1000 kW	1	1	1	1	1	1	1	1	1

Tab. 9.9 shows the specific air emissions assumed for the modelled wood heating systems. Carbon dioxide is absorbed during tree growth. The total amount of carbon stored in the wood, calculated assuming 49.4% carbon in dry wood, is assumed to be re-emitted during combustion as CO_2 or CO.

9.4.6 Operation of cogeneration plants

Particulates, NO_x, and CO emission data of the cogeneration plants are based on direct measurements at the specific plants (Tab. 9.10). Emission rates of other species are assumed equal to the corresponding values for the 1000 kW wood chip industrial boiler. The efficiency of the baghouse filter for the reduction of particle emissions is assumed to be 90% supplementary to Multi-Cyclone. The filter uses 8% of the electricity produced. All particles are assumed to be smaller than 2.5 μm, based on (Wieser et al. 2001).[12] The Selective Non Catalytic Reduction (SNCR), which works with urea as reducing agent, reduces NO_x emissions by 50%.

[11] Based on personal information from Mr. Brenn, EMPA Dübendorf, June 2002.

[12] Also personal communication with Mr. Brenn, EMPA Dübendorf, June 2002.

Tab. 9.9 Emission data of wood heating systems* [kg/MJ useful energy]

kg/MJ useful energy	Wood log heating 6 kW	Wood log heating 30 kW	Wood log heating 100 kW	Wood chips heating 50 kW	Wood chips heating 300 kW	Wood chips heating 1000 kW	Pellets heating 15 kW	Pellets heating 50 kW
Acetaldehyde	8.13E-8	8.97E-8	8.71E-8	7.63E-8	7.44E-8	7.18E-8	7.44E-8	7.18E-8
Ammonia	2.31E-6	2.54E-6	2.47E-6	2.16E-6	2.11E-6	2.04E-6	2.11E-6	2.04E-6
Arsenic	1.33E-9	1.47E-9	1.43E-9	1.25E-9	1.22E-9	1.18E-9	1.22E-9	1.18E-9
Benzene	1.21E-6	1.34E-6	1.30E-6	1.14E-6	1.11E-6	1.07E-6	1.11E-6	1.07E-6
Benzene, ethyl-	4.00E-8	4.41E-8	4.29E-8	3.75E-8	3.66E-8	3.53E-8	3.66E-8	3.53E-8
Benzene, hexachloro-	9.60E-15	1.06E-14	1.03E-14	9.00E-15	8.78E-15	8.47E-15	8.78E-15	8.47E-15
Benzo(a)pyrene	6.67E-10	7.35E-10	7.14E-10	6.25E-10	6.10E-10	5.88E-10	6.10E-10	5.88E-10
Bromine	8.00E-8	8.82E-8	8.57E-8	7.50E-8	7.32E-8	7.06E-8	7.32E-8	7.06E-8
Cadmium	9.33E-10	1.03E-9	1.00E-9	8.75E-10	8.54E-10	8.24E-10	8.54E-10	8.24E-10
Calcium	7.80E-6	8.60E-6	8.36E-6	7.31E-6	7.13E-6	6.88E-6	7.13E-6	6.88E-6
Carbon dioxide, biogenic							1.18E-1	1.14E-1
Softwood	1.23E-1	1.40E-1	1.37E-1	1.27E-1	1.24E-1	1.20E-1		
Hardwood	1.29E-1	1.47E-1	1.43E-1	1.34E-1	1.30E-1	1.26E-1		
Mixed	1.25E-1	1.42E-1	1.38E-1	1.29E-1	1.26E-1	1.22E-1		
Carbon monoxide, biogenic	3.07E-3	5.88E-4	4.84E-4	1.48E-4	5.85E-5	4.82E-5	1.17E-4	7.65E-5
Chlorine	2.40E-7	2.65E-7	2.57E-7	2.25E-7	2.20E-7	2.12E-7	2.20E-7	2.12E-7
Chromium	5.28E-9	5.82E-9	5.66E-9	4.95E-9	4.83E-9	4.66E-9	4.83E-9	4.66E-9
Chromium VI**	5.33E-11	5.88E-11	5.71E-11	5.00E-11	4.88E-11	4.71E-11	4.88E-11	4.71E-11
Copper	2.93E-8	3.24E-8	3.14E-8	2.75E-8	2.68E-8	2.59E-8	2.68E-8	2.59E-8
Dinitrogen monoxide	9.33E-6	5.88E-6	4.29E-6	3.75E-6	3.05E-6	2.71E-6	3.66E-6	2.94E-6
Dioxins***	4.13E-14	4.56E-14	4.43E-14	3.88E-14	3.78E-14	3.65E-14	3.78E-14	3.65E-14
Fluorine	6.67E-8	7.35E-8	7.14E-8	6.25E-8	6.10E-8	5.88E-8	6.10E-8	5.88E-8
Formaldehyde	1.73E-7	1.91E-7	1.86E-7	1.63E-7	1.59E-7	1.53E-7	1.59E-7	1.53E-7
Heat, waste	1.43E+0	1.59E+0	1.54E+0	1.36E+0	1.32E+0	1.28E+0	1.32E+0	1.28E+0
Hydrocarbons, aliphatic, alkanes, unspecified	1.21E-6	1.34E-6	1.30E-6	1.14E-6	1.11E-6	1.07E-6	1.11E-6	1.07E-6
Hydrocarbons, aliphatic, unsaturated	4.13E-6	4.56E-6	4.43E-6	3.88E-6	3.78E-6	3.65E-6	3.78E-6	3.65E-6
Lead	3.33E-8	3.68E-8	3.57E-8	3.13E-8	3.05E-8	2.94E-8	3.05E-8	2.94E-8
Magnesium	4.80E-7	5.29E-7	5.14E-7	4.50E-7	4.39E-7	4.24E-7	4.39E-7	4.24E-7
Manganese	2.27E-7	2.50E-7	2.43E-7	2.13E-7	2.07E-7	2.00E-7	2.07E-7	2.00E-7
Mercury	4.00E-10	4.41E-10	4.29E-10	3.75E-10	3.66E-10	3.53E-10	3.66E-10	3.53E-10
Methane, biogenic	2.67E-5	2.21E-5	2.00E-5	8.75E-7	4.88E-7	4.71E-7	4.88E-7	3.53E-7
m-Xylene	1.60E-7	1.76E-7	1.71E-7	1.50E-7	1.46E-7	1.41E-7	1.46E-7	1.41E-7
Nickel	8.00E-9	8.82E-9	8.57E-9	7.50E-9	7.32E-9	7.06E-9	7.32E-9	7.06E-9
Nitrogen oxides							8.54E-5	8.71E-5
Softwood	2.03E-4	1.63E-4	1.46E-4	1.30E-4	1.24E-4	1.14E-4		
Hardwood	2.52E-4	2.01E-4	1.81E-4	1.63E-4	1.55E-4	1.44E-4		
Mixed	2.13E-4	1.72E-4	1.54E-4	1.38E-4	1.30E-4	1.22E-4		
NMVOC	1.29E-5	1.07E-5	8.29E-6	1.13E-6	7.32E-7	7.06E-7	2.80E-6	1.76E-6
PAH, polycyclic aromatic hydrocarbons	1.48E-8	1.63E-8	1.59E-8	1.39E-8	1.35E-8	1.31E-8	1.35E-8	1.31E-8
Particulates, < 2.5 um	1.56E-4	5.88E-5	4.71E-5	4.25E-5	5.61E-5	7.18E-5	3.17E-5	2.35E-5
Phenol, pentachloro-	1.08E-11	1.19E-11	1.16E-11	1.01E-11	9.88E-12	9.53E-12	9.88E-12	9.53E-12
Phosphorus	4.00E-7	4.41E-7	4.29E-7	3.75E-7	3.66E-7	3.53E-7	3.66E-7	3.53E-7
Potassium	3.12E-5	3.44E-5	3.34E-5	2.93E-5	2.85E-5	2.75E-5	2.85E-5	2.75E-5
Sodium	1.73E-6	1.91E-6	1.86E-6	1.63E-6	1.59E-6	1.53E-6	1.59E-6	1.53E-6
Sulfur dioxide	3.33E-6	3.68E-6	3.57E-6	3.13E-6	3.05E-6	2.94E-6	3.05E-6	2.94E-6
Toluene	4.00E-7	4.41E-7	4.29E-7	3.75E-7	3.66E-7	3.53E-7	3.66E-7	3.53E-7
Zinc	4.00E-7	4.41E-7	4.29E-7	3.75E-7	3.66E-7	3.53E-7	3.66E-7	3.53E-7

* Same emission factors for industrial wood chips and chips from forest.

** 1% of total chromium emissions is assumed to be emitted as CrVI.

*** Measured as 2,3,7,8-terachlordibenzo-p-dioxin.

Tab. 9.10 Emission data for partcles, NO_x, and CO for the modelled cogeneration plants [mg/MJ_{in}], based on measurements and assumptions for emission control.

$[kg/MJ_{in}]$	Cogeneration 1400 kW Multi-Zyclone	Cogeneration 1400 kW Emission control*	Cogeneration 6400 kW Multi-Zyclone	Cogeneration 6400 kW Emission control *
Particle	1.11E-4	1.10E-5	4.50E-5	5.00E-6
NO_x	1.12E-4	5.60E-5	8.80E-5	4.40E-5
CO	3.50E-5	3.50E-5	7.00E-6	7.00E-6

*Assumptions for emission control: Efficiency of particle reduction 90%, efficiency of NO_x reduction 50%.

Combustion residues

It is assumed that after combustion, 1% of the dry mass of logs and chips and 0.5% of the dry mass of pellets is left as ash. Since only the combustion of untreated wood is addressed in this study, wood ash does not contain potentially harmful heavy metals or other toxic substances. Three different ash disposal routes are accounted for: to municipal incineration through household rubbish collection; to landfarming; and, to sanitary landfill. For boilers up to 50 kW capacity, 50% of the ash is assumed to be delivered to municipal incineration and 50% to landfarming. Fifty percent of wood ash produced at furnaces with higher heat capacity is assumed to be disposed of in sanitary landfill, 25% in landfarming, and 25% sent to municipal incineration. The fate of disposed ash is described in (Doka 2003).

9.4.7 Allocation for cogeneration plants

Since cogeneration plants produce heat and electricity, their environmental burdens have to be allocated to these products. Various alternatives exist for allocation. Since the choice has subjective aspects, the three alternative allocation criteria "heat", "exergy", and "energy" are offered to the user of the ecoinvent database.

Allocation heat means that all burdens are entirely allocated to the produced heat, under the basic assumption that heat production is the main purpose of the plant and electricity is an emission-free byproduct. In case of the two analysed cogeneration plants this would make sense, because they are operated with low electric efficiency. Allocation energy means that all elementary flows are allocated to heat and electricity with the share of energy provided as heat or electricity. Allocation factors for exergy depend on electric and thermal efficiencies, ambient temperature, and temperature of the delivered heat. Calculation of these factors is given in the Appendix. Tab. 9.11 shows the allocation factors used for wood cogeneration.

Tab. 9.11 Allocation factors for wood cogeneration

	Cogeneration plant 6400 kW				**Cogeneration plant 1400 kW**			
	Multi-Cyclone		Emission control		Multi-Cyclone		Emission control	
Basis	heat	electricity	heat	electricity	heat	electricity	heat	electricity
Exergy [exergetic value]	0.335	1	0.335	1	0.207	1	0.207	1
Energy [%]	0.903	0.097	0.907	0.093	0.960	0.040	0.962	0.038
Heat („motivation")	1	0	1	0	1	0	1	0
Allocation factors								
Exergy	**0.757**	**0.243**	**0.765**	**0.235**	**0.833**	**0.167**	**0.839**	**0.161**
Energy	**0.903**	**0.097**	**0.907**	**0.093**	**0.960**	**0.040**	**0.962**	**0.038**
Heat	**1**	**0**	**1**	**0**	**1**	**0**	**1**	**0**

9.5 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

9.5.1 Selected Results

Tab. 9.12 through Tab. 9.15 show selected cumulative LCI results and the cumulative energy demand for heat production at all modelled conventional wood heating systems burning the Swiss commercial mix of hardwood and softwood. Results for hardwood and softwood only are available in the Geman report and the ecoinvent database.

Tab. 9.12 Selected LCI results and cumulative energy demand for heat production at wood log boilers 100/30/6 kW, mixed wood

		Name		heat, mixed logs, at furnace 100kW	heat, mixed logs, at furnace 30kW	heat, mixed logs, at wood heater 6kW
		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	4.68E-02	5.06E-02	4.12E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.25E-02	3.46E-02	7.63E-03
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.12E-02	1.19E-02	3.02E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.23E-04	2.43E-04	9.32E-05
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.55E+00	1.59E+00	1.44E+00
LCI results						
resource	Land occupation	total	m2a	8.24E-02	8.48E-02	7.66E-02
air	Carbon dioxide, fossil	total	kg	3.10E-03	3.36E-03	2.67E-03
air	NMVOC	total	kg	3.47E-05	3.81E-05	3.75E-05
air	Nitrogen oxides	total	kg	2.15E-04	2.35E-04	2.70E-04
air	Sulphur dioxide	total	kg	1.03E-05	1.12E-05	9.01E-06
air	Particulates, < 2.5 um	total	kg	5.40E-05	6.59E-05	1.62E-04
water	BOD	total	kg	1.41E-05	1.70E-05	1.58E-05
soil	Cadmium	total	kg	2.86E-09	5.86E-09	5.30E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.39E-01	1.42E-01	1.25E-01
air	Methane, biogenic	total	kg	2.01E-05	2.21E-05	2.66E-05
air	Dinitrogen monoxide	total	kg	4.45E-06	6.04E-06	9.43E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	2.64E-06	3.10E-06	2.93E-06
air	Particulates, > 10 um	total	kg	3.82E-06	4.37E-06	3.70E-06

Tab. 9.13 Selected LCI results and cumulative energy demand for heat production at wood chips boilers 1000/300/50 kW, mixed chips from forest

		Name		heat, mixed chips from forest, at furnace 1000kW	heat, mixed chips from forest, at furnace 300kW	heat, mixed chips from forest, at furnace 50kW
		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	6.45E-02	6.24E-02	7.18E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.90E-02	4.03E-02	4.29E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.28E-02	1.33E-02	1.42E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.79E-04	2.87E-04	3.09E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.36E+00	1.41E+00	1.44E+00
LCI results						
resource	Land occupation	total	m2a	5.89E-02	6.09E-02	6.26E-02
air	Carbon dioxide, fossil	total	kg	4.31E-03	4.35E-03	5.65E-03
air	NMVOC	total	kg	2.47E-05	2.49E-05	2.66E-05
air	Nitrogen oxides	total	kg	1.89E-04	1.96E-04	2.10E-04
air	Sulphur dioxide	total	kg	1.07E-05	1.08E-05	1.20E-05
air	Particulates, < 2.5 um	total	kg	7.86E-05	6.31E-05	5.10E-05
water	BOD	total	kg	1.52E-05	1.50E-05	1.77E-05
soil	Cadmium	total	kg	2.06E-09	2.13E-09	4.35E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.23E-01	1.27E-01	1.30E-01
air	Methane, biogenic	total	kg	5.63E-07	5.82E-07	9.03E-07
air	Dinitrogen monoxide	total	kg	2.91E-06	3.24E-06	3.96E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	3.62E-06	5.93E-06	1.54E-05
air	Particulates, > 10 um	total	kg	5.51E-06	7.99E-06	1.86E-05

Tab. 9.14 Selected LCI results and cumulative energy demand for heat production at wood chips boilers 1000/300/50 kW, mixed chips from industry

		Name		heat, mixed chips from industry, at furnace 1000kW	heat, mixed chips from industry, at furnace 300kW	heat, mixed chips from industry, at furnace 50kW
		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	4.03E-02	3.80E-02	4.68E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	4.18E-02	4.32E-02	4.58E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.23E-02	1.27E-02	1.36E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	3.99E-04	4.11E-04	4.36E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.29E+00	1.34E+00	1.37E+00
LCI results						
resource	Land occupation	total	m2a	1.90E-02	1.96E-02	2.03E-02
air	Carbon dioxide, fossil	total	kg	2.91E-03	2.95E-03	4.20E-03
air	NMVOC	total	kg	1.33E-05	1.31E-05	1.46E-05
air	Nitrogen oxides	total	kg	1.42E-04	1.48E-04	1.61E-04
air	Sulphur dioxide	total	kg	9.22E-06	9.34E-06	1.05E-05
air	Particulates, < 2.5 um	total	kg	7.39E-05	5.82E-05	4.61E-05
water	BOD	total	kg	7.33E-06	6.86E-06	9.41E-06
soil	Cadmium	total	kg	2.06E-09	2.13E-09	4.34E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.16E-01	1.20E-01	1.23E-01
air	Methane, biogenic	total	kg	5.62E-07	5.81E-07	9.02E-07
air	Dinitrogen monoxide	total	kg	2.85E-06	3.18E-06	3.90E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	2.40E-06	4.68E-06	1.41E-05
air	Particulates, > 10 um	total	kg	4.20E-06	6.65E-06	1.72E-05

Tab. 9.15 Selected LCI results and cumulative energy demand for heat production at pellets boilers 15/50 kW

		Name		heat, wood pellets, at furnace 15kW	heat, wood pellets, at furnace 50kW
		Location		CH	CH
		Unit	Unit	MJ	MJ
		Infrastructure		0	0
LCIA results					
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.92E-01	1.79E-01
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.27E-01	1.21E-01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.60E-02	2.46E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.48E-03	2.36E-03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.32E+00	1.27E+00
LCI results					
resource	Land occupation	total	m2a	3.39E-02	3.28E-02
air	Carbon dioxide, fossil	total	kg	1.45E-02	1.35E-02
air	NMVOC	total	kg	2.57E-05	2.35E-05
air	Nitrogen oxides	total	kg	1.52E-04	1.50E-04
air	Sulphur dioxide	total	kg	4.47E-05	4.20E-05
air	Particulates, < 2.5 um	total	kg	4.01E-05	3.07E-05
water	BOD	total	kg	2.40E-05	2.09E-05
soil	Cadmium	total	kg	2.11E-09	2.03E-09
Further LCI results					
air	Carbon dioxide, biogenic	total	kg	1.19E-01	1.15E-01
air	Methane, biogenic	total	kg	5.46E-07	4.08E-07
air	Dinitrogen monoxide	total	kg	4.23E-06	3.49E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	1.38E-05	1.02E-05
air	Particulates, > 10 um	total	kg	2.24E-05	1.82E-05

Tab. 9.16 through Tab. 9.19 show selected cumulative LCI results and the cumulative energy demand for heat production at the modelled cogeneration plants for all three allocation criteria. Results for electricity production are available in the database.

Tab. 9.16 Selected LCI results and cumulative energy demand for heat production at wood cogeneration 6400 kW, allocation energy, exergy, and heat

		Name		heat, at cogen 6400kWth, wood, allocation energy	heat, at cogen 6400kWth, wood, allocation exergy	heat, at cogen 6400kWth, wood, allocation heat
		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	3.74E-02	3.14E-02	4.14E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.09E-02	9.11E-03	1.20E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.12E-03	1.77E-03	2.34E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.31E-04	1.94E-04	2.56E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.29E+00	1.08E+00	1.43E+00
LCI results						
resource	Land occupation	total	m2a	1.91E-02	1.59E-02	2.11E-02
air	Carbon dioxide, fossil	total	kg	2.63E-03	2.21E-03	2.91E-03
air	NMVOC	total	kg	1.37E-05	1.14E-05	1.51E-05
air	Nitrogen oxides	total	kg	1.24E-04	1.05E-04	1.38E-04
air	Sulphur dioxide	total	kg	9.20E-06	7.72E-06	1.02E-05
air	Particulates, < 2.5 um	total	kg	5.49E-05	4.60E-05	6.07E-05
water	BOD	total	kg	1.72E-05	1.44E-05	1.91E-05
soil	Cadmium	total	kg	2.27E-09	1.90E-09	2.51E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.23E-01	1.03E-01	1.36E-01
air	Methane, biogenic	total	kg	1.05E-06	8.84E-07	1.16E-06
air	Dinitrogen monoxide	total	kg	2.95E-06	2.48E-06	3.27E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	2.51E-06	2.10E-06	2.78E-06
air	Particulates, > 10 um	total	kg	3.89E-06	3.25E-06	4.30E-06

Tab. 9.17 Selected LCI results and cumulative energy demand for heat production at wood cogeneration 6400 kW, emission control, allocation energy, exergy, and heat

		Name		heat, at cogen 6400kWth, wood, emission control, allocation energy	heat, at cogen 6400kWth, wood, emission control, allocation exergy	heat, at cogen 6400kWth, wood, emission control, allocation heat
		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	3.96E-02	3.34E-02	4.36E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.10E-02	9.29E-03	1.21E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.15E-03	1.81E-03	2.37E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.35E-04	1.98E-04	2.59E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.30E+00	1.09E+00	1.43E+00
LCI results						
resource	Land occupation	total	m2a	1.91E-02	1.61E-02	2.11E-02
air	Carbon dioxide, fossil	total	kg	2.73E-03	2.30E-03	3.01E-03
air	NMVOC	total	kg	1.38E-05	1.16E-05	1.52E-05
air	Nitrogen oxides	total	kg	7.33E-05	6.19E-05	8.09E-05
air	Sulphur dioxide	total	kg	9.37E-06	7.91E-06	1.03E-05
air	Particulates, < 2.5 um	total	kg	7.95E-06	6.70E-06	8.77E-06
water	BOD	total	kg	1.74E-05	1.47E-05	1.92E-05
soil	Cadmium	total	kg	2.28E-09	1.92E-09	2.51E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.23E-01	1.04E-01	1.36E-01
air	Methane, biogenic	total	kg	1.06E-06	8.93E-07	1.16E-06
air	Dinitrogen monoxide	total	kg	2.63E-05	2.22E-05	2.90E-05
air	Particulates, > 2.5 um, and < 10um	total	kg	2.55E-06	2.15E-06	2.81E-06
air	Particulates, > 10 um	total	kg	3.95E-06	3.34E-06	4.36E-06

Tab. 9.18 Selected LCI results and cumulative energy demand for heat production at wood cogeneration 1400 kW, allocation energy, exergy, and heat

		Name		heat, at cogen ORC 1400kWth, wood, allocation energy	heat, at cogen ORC 1400kWth, wood, allocation exergy	heat, at cogen ORC 1400kWth, wood, allocation heat
		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	4.10E-02	3.55E-02	4.27E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.19E-02	1.03E-02	1.24E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.36E-03	2.05E-03	2.46E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.50E-04	2.17E-04	2.60E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.37E+00	1.19E+00	1.43E+00
LCI results						
resource	Land occupation	total	m2a	2.02E-02	1.76E-02	2.11E-02
air	Carbon dioxide, fossil	total	kg	2.88E-03	2.50E-03	2.99E-03
air	NMVOC	total	kg	1.46E-05	1.27E-05	1.52E-05
air	Nitrogen oxides	total	kg	1.63E-04	1.41E-04	1.70E-04
air	Sulphur dioxide	total	kg	1.01E-05	8.75E-06	1.05E-05
air	Particulates, < 2.5 um	total	kg	1.41E-04	1.22E-04	1.47E-04
water	BOD	total	kg	2.00E-05	1.74E-05	2.08E-05
soil	Cadmium	total	kg	2.42E-09	2.10E-09	2.52E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.30E-01	1.13E-01	1.36E-01
air	Methane, biogenic	total	kg	1.20E-06	1.04E-06	1.24E-06
air	Dinitrogen monoxide	total	kg	3.16E-06	2.75E-06	3.29E-06
air	Particulates, > 2.5 um, and < 10um	total	kg	3.02E-06	2.62E-06	3.15E-06
air	Particulates, > 10 um	total	kg	4.54E-06	3.94E-06	4.73E-06

Tab. 9.19 Selected LCI results and cumulative energy demand for heat production at wood cogeneration 1400 kW, emission control, allocation energy, exergy, and heat

		Name		heat, at cogen ORC 1400kWth, wood, emission control, allocation energy	heat, at cogen ORC 1400kWth, wood, emission control, allocation exergy	heat, at cogen ORC 1400kWth, wood, emission control, allocation heat
		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	4.37E-02	3.82E-02	4.55E-02
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.21E-02	1.05E-02	1.26E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.39E-03	2.09E-03	2.49E-03
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.54E-04	2.21E-04	2.64E-04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.37E+00	1.20E+00	1.43E+00
LCI results						
resource	Land occupation	total	m2a	2.03E-02	1.77E-02	2.11E-02
air	Carbon dioxide, fossil	total	kg	3.01E-03	2.63E-03	3.13E-03
air	NMVOC	total	kg	1.47E-05	1.28E-05	1.53E-05
air	Nitrogen oxides	total	kg	9.33E-05	8.13E-05	9.68E-05
air	Sulphur dioxide	total	kg	1.03E-05	8.96E-06	1.07E-05
air	Particulates, < 2.5 um	total	kg	1.60E-05	1.40E-05	1.67E-05
water	BOD	total	kg	2.02E-05	1.76E-05	2.11E-05
soil	Cadmium	total	kg	2.42E-09	2.11E-09	2.52E-09
Further LCI results						
air	Carbon dioxide, biogenic	total	kg	1.31E-01	1.14E-01	1.36E-01
air	Methane, biogenic	total	kg	1.20E-06	1.05E-06	1.24E-06
air	Dinitrogen monoxide	total	kg	2.78E-05	2.43E-05	2.89E-05
air	Particulates, > 2.5 um, and < 10um	total	kg	3.07E-06	2.67E-06	3.19E-06
air	Particulates, > 10 um	total	kg	4.62E-06	4.03E-06	4.80E-06

9.5.2 Analysis

The analysis of the cumulative results for conventional wood heating and cogeneration systems shows that in case of species released by direct combustion of wood in boilers, the relative contributions from the operation phase are substantially higher than the contributions to total from other parts of the energy chain. Hence, for these species the differences among the modelled systems are basically controlled by the specific direct emission levels. For pellet boilers this effect is somewhat reduced, as shown below.

In this analysis, cumulative emissions are separated into contributions from different parts of the energy chain. The emissions from wood combustion are identified in the following graphs with “Direct”. “Fuel Supply” stands for contributions from the upstream chain, as modelled in (Werner et al. 2003); these include all processes up to the production of wood fuels. “Electrcity for operation” represents contributions originating in the electricity requirements during operation of the heating systems. “Boiler” stands for contributions from the production of the infrastructure, including the wood boiler itself and chip or pellet storage room. ”Transport of wood fuels to consumer” means contributions from the transport of wood logs, chips, or pellets from forest, industry, or storehouse to consumers. “Waste disposal” represents contributions from wood ash disposal.

In general, energy requirements for operation, material and energy requirements for infrastructure, and disposal of the wood ash do not contribute important amounts to cumulative results.

Particle (<2.5 µm) and NO_x emissions are two of the major environmental burdens from wood combustion. Cumulative emissions of particles (<2.5 µm) and NO_x are shown in Fig. 9.2 and Fig. 9.3, respectively. Direct particle (<2.5 µm) and NO_x emissions from pellet heating systems are about 40% to 50% lower than the ones from boilers of comparable capacity burning other wood fuels. The explanation lies in the different fuel characteristics. Pellets are very homogenous, thus allowing a very uniform combustion with reduced particle emissions. Lower NO_x emissions from pellet boilers originate from lower nitrogen content of the pellets (thermal formation of NO_x is minor compared with oxidation of nitrogen in the wood). The reason is that wood chips and logs include bark, which has a higher density of nitrogen, whereas pellets are often made without bark.[13]

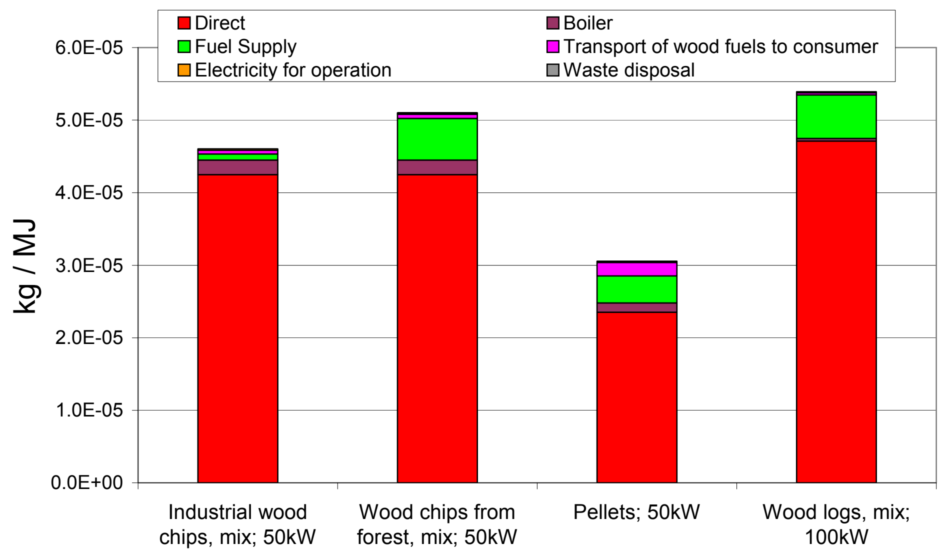

Fig. 9.2 Particle emissions <2.5 µm from different wood heating systems of the 50/100 kW class [kg/MJ useful energy].

[13] This assumption is based on a personal communication with T. Nussbaumer, VERENUM Zürich, in May 2002.

The advantage of lower direct emissions from pellet heating systems is somewhat reduced by the burdens associated with pellet manufacturing and the assumed higher transport distances. This effect can be easily observed analysing total fossil CO_2 emissions and release of particles >2.5 µm, which are assumed to be not directly emitted by the boilers. These substances are mostly released by wood fuel supply chain and transports. Moreover, total net greenhouse gas emissions are highest for pellet heating systems for the same reason. Fig. 9.4 shows the net greenhouse gas emissions for the 50/100 kW class boilers.

Fig. 9.3 **NO_x emissions from different wood heating systems of the 50/100 kW class [kg/MJ useful energy].**

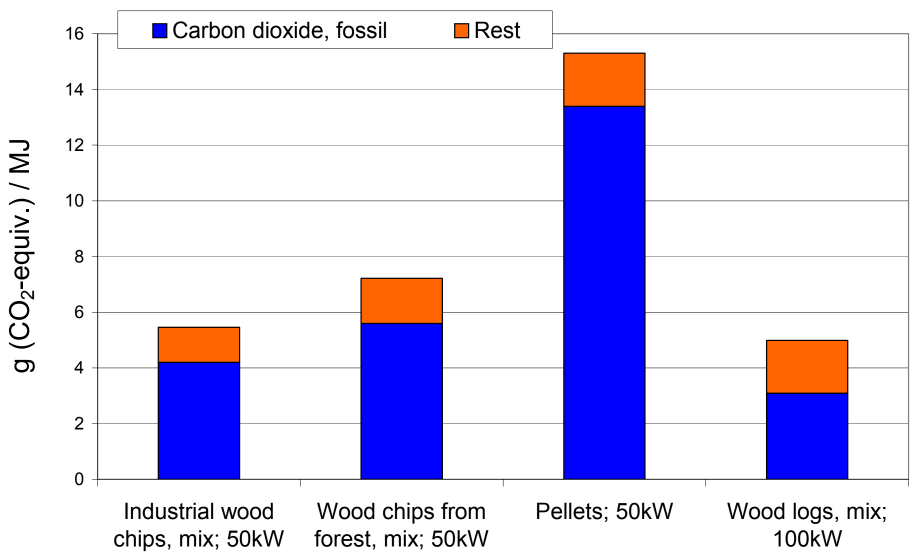

Fig. 9.4 **Net greenhouse gas emissions from different wood heating systems of the 50/100 kW class [g (CO_2-equiv.)/MJ useful energy].**

As an example representative for other elementary flows, the analysis of cumulative NO_x emissions shows the difference between the supply chain of industrial wood chips compared with wood chips from forest. The assumption of Werner et al. (2003) that the bulk of requirements and emissions from wood harvesting and processing is almost fully allocated to other economically more valuable wood products rather than to industrial residue wood leads to lower total burdens from the production of industrial wood chips compared to the production of forest wood chips.

Differences between cumulative results of hardwood and softwood heating systems originate from different direct NO_x emissions and from different energy content per volume of hardwood and softwood. Specific (per unit of energy) NO_x emissions are about 25% higher for hardwood combustion than for softwood combustion. Since material and energy requirements and associated environmental burdens for fuel supply are depending on the volume of wood, supply of hardwood causes lower specific burdens, because energy content per volume of hardwood is higher than energy content per volume of softwood.

Differences of total burdens among the modelled capacity classes can also be primarily attributed to direct emissions of the boilers, depending on the efficiencies. Due to incomplete combustion and generally smaller capacity, wood log boilers have higher particle, CO, and VOC emissions than wood chip and pellet heating systems.

Since direct particle (<2.5 µm) and NO_x emissions from wood combustion are substantial, the reductions obtained for cogeneration systems through the baghouse filter and the SNCR lead to substantial reductions of the total emissions, compared with the plants using multi-cyclone. Burdens associated with the increased internal electricity uses for the operation of the baghouse filter and with the requirements of urea for the SNCR give negligible contributions to cumulative results. The only apparent disadvantage of the assumed emission control technologies is the higher N_2O emission due to the use of urea as reduction agent, which contributes about 40% to total net greenhouse gas emissions of nearly 19 g (CO_2-equiv.)/MJ (GWP 100a) for both cogeneration plants in case of allocation heat.

9.6 Conclusions and outlook

The most important conclusion from the analysis of the cumulative results for the heat production at the different modelled wood heating systems is that key factors remain the direct environmental burdens from the combustion of wood fuels and the plant efficiency. The upstream processes and waste disposal contribute marginally for most of the burdens. Although pellet production necessitates more energy than the production of other wood fuels, pellet heating systems still have lower cumulative specific emissions than wood chips and wood log heating systems, with the notable exception of net CO_2.

The assumption of (Werner et al. 2003) concerning the allocation of burdens to economically more valuable industrial wood products rather than to the raw material for industrial wood chips leads to better results for heating with industrial wood chips than for heating with wood chips directly from forest. This assumption is valid as long as only residual wood is used for the industrial wood chips. In case of rising importance of wood heating, the current allocation might need to be reconsidered.

The assumed correction factors to account for differences between measurements in controlled conditions and actual plant operation are rather rough estimations. Results from field measurements of actual emissions for all species of interest would be useful to reduce the uncertainties.

In order to reduce the relatively high emissions of NO_x and particles from wood heating systems, the introduction of pollution control systems would be beneficial, though at present economically viable for large units only. Due to the very low electric efficiency for the current operation of the modelled cogeneration plants, the cumulative results for electricity production should not be used for comparison with other electricity systems.

Considering likely further improvements in efficiency, though not dramatic, the assessment of wood technologies should be updated in the future. Future assessments should also include wood gasification for the growing interest in this advanced technology.

9.7 References

Bauer 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.
BfE 2001	BfE, Bundesamt für Energie (2001) Überblick über den Energieverbrauch in der Schweiz im Jahr 2000. Auszug aus der Schweizerischen Gesamtenergiestatistik 2000. Bern.
BfS/BUWAL 2000	BfS, Bundesamt für Statistik / BUWAL, Bundesamt für Umwelt, Wald und Landschaft (Hrsg.) (2000) Forest and Wood. Yearbook 2000. Neuchâtel, CH.
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, Dübendorf, CH, retrieved from: www.ecoinvent.ch.
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.
Wieser et al. 2001	Wieser U., Gaegauf C., Macquat Y. (2001) Partikelemissionen aus Holzfeuerungen. Untersuchung der Partikelfrachten in Holzfeuerungsabgasen unter Praxisbedingungen. Im Auftrag von BUWAL und BfE. Langenbruck, Schweiz.

9.8 Appendix

Allocation factors used for wood cogeneration systems (see chapter 9.4.7) are calculated on the basis of the following data and formulas, shown in Tab. 9.20:

Tab. 9.20 Basic data for the calculation of allocation factors used in this study for wood cogeneration systems

	Cogeneration 6400 kW				Cogeneration 1400 kW			
	Multi-Cyclone		Emission control		Multi-Cyclone		Emission control	
Allocation	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
Electricity	**0.097**	**0.243**	**0.093**	**0.235**	**0.040**	**0.167**	**0.038**	**0.161**
Heat	**0.903**	**0.757**	**0.907**	**0.765**	**0.960**	**0.833**	**0.962**	**0.839**
Temperature of hot water T_o [°K]		433		433		363		363
Ambient temperature T_u [°K]		288		288		288		288
η_{el}		0.0826		0.0789		0.0318		0.0304
η_{th}		0.7673		0.7673		0.7684		0.7684
Exerget. Rating Electrcity ς_{el}		1		1		1		1
Exerget. Rating Heat ς_{th}		0.3349		0.3349		0.2066		0.2066
Σ_{site}		0.3396		0.3359		0.1906		0.1892
$\text{Allocation}_{\text{Electricity}}$		0.2432		0.2349		0.1668		0.1607
$\text{Allocation}_{\text{Heat}}$		0.7567		0.7650		0.8329		0.8391

$$\varsigma_{th} = (T_o - T_u) / T_o$$

$$\varsigma_{site} = \varsigma_{el} \cdot \eta_{el} + \varsigma_{th} \cdot \eta_{th}$$

$$\text{Allocation}_{\text{Electricity}} = \varsigma_{el} \cdot \eta_{el} / \varsigma_{site}$$

$$\text{Allokation}_{\text{Heat}} = \varsigma_{th} \cdot \eta_{th} / \varsigma_{site}$$

10 Heat Pumps

Author: Thomas Heck, PSI

10.1 Introduction

Currently about 40% of new buildings in Switzerland are equipped with a heat pump. About 52% of the heat pumps sold in Switzerland in year 2002 are using the ambient air, about 43% the ground, and about 5% water as heat reservoir (Beyeler 2003).

Here, only a short overview of the inventory and the results is provided. For further details, the reader may refer to the full report (Heck 2004).

10.2 System description

Two wide-spread types of heat pumps are modelled: an air/water heat pump and a brine/water heat pump. An air/water heat pump uses the heat of the ambient air and supplies the heat to the water of a hydronic heat distribution system. A brine/water heat pump is connected to a borehole heat exchanger gaining heat from the ground. For both types of heat pumps a low temperature hydronic floor heating system was assumed for the distribution of heat within the house. For modelling, 10 kW heat pumps for one-family houses are assumed. Datasets are provided both for heat at heat pump before heat distribution and for heat at radiator after heat distribution. Two locations are considered: Switzerland and average Europe. The essential difference for the two locations is the electricity mix (Frischknecht & Faist Emmenegger 2003). The Swiss electricity supply mix has been used for the Swiss heat pumps, the UCTE mix for the European heat pumps. It was assumed that the environmental boundary conditions are the same in both cases.

An essential parameter for heat pumps is the seasonal performance factor (SPF). The SPF as used in this study is defined as the ratio between the quantity of heat supplied by the heat pump (excluding buffer losses in case there is a buffer) and the amount of electricity used by the heat pump installation including all auxiliaries. A recent field analysis of Swiss heat pump installations has been used to estimate the seasonal performance factors. The values for the Swiss SPF have been applied also to average European conditions. Considering new heat pumps installed during year 1998 in new buildings in Switzerland, air/water heat pumps had an SPF of about 2.8 and brine/water heat pumps had an SPF of about 3.9 (Erb M. & P. 2001). Reverse mode of operation (cooling) has not been considered.

A life time of about 20 years was assumed for heat pumps after (Hess 1993; Lovvorn 2001). The production of the refrigerant was modelled as well. Only the widely used (WPZ 2003) refrigerant R134a was considered. Based on emission rates listed in (Frischknecht 1999), it was assumed that about 6% of the refrigerant in the heat pump is emitted annually due to leakages. The refrigerant filling of the heat pump was assumed to be about 3 kg for the brine/water heat pump and about 4.8 kg for the air/water heat pump.

Tab. 10.1 lists the names of the datasets available in the ecoinvent database for heat from 10 kW heat pumps.

Tab. 10.1 Ecoinvent datasets for heat (unit MJ) from 10 kW heat pumps.

Name	Country/ Region
heat, borehole heat exchanger, at brine/water heat pump 10kW	CH / RER
heat, borehole heat exchanger, brine/water heat pump 10kW, at heat radiator	CH / RER
heat, at air-water heat pump 10kW	CH / RER
heat, air-water heat pump 10kW, at heat radiator	CH / RER

10.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

The following tables show selected LCI results and cumulative energy demands for heat from 10 kW heat pumps. Tab. 10.2 lists results for Switzerland and Europe without heat distribution. Tab. 10.3 shows results including heat distribution in the house.

Tab. 10.2 Selected LCI results and cumulative energy demands for heat at 10 kW heat pumps without heat distribution.

		Name		heat, borehole heat exchanger, at brine-water heat pump 10kW	heat, borehole heat exchanger, at brine-water heat pump 10kW	heat, at air-water heat pump 10kW	heat, at air-water heat pump 10kW
		Location		CH	RER	CH	RER
		Unit	Unit	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.14	0.48	0.17	0.65
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.47	0.38	0.66	0.53
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.15	0.06	0.21	0.08
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.75	0.75	0.00	0.01
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00	0.01	0.00	0.01
LCI results							
resource	Land occupation	total	m2a	6.5E-4	8.9E-4	9.0E-4	1.2E-3
air	Carbon dioxide, fossil	total	kg	1.0E-2	3.7E-2	1.3E-2	5.1E-2
air	NMVOC	total	kg	9.4E-6	1.5E-5	9.7E-6	1.8E-5
air	Nitrogen oxides	total	kg	3.6E-5	8.8E-5	2.4E-5	9.6E-5
air	Sulphur dioxide	total	kg	2.5E-5	1.5E-4	3.3E-5	2.1E-4
air	Particulates, < 2.5 um	total	kg	4.8E-6	1.2E-5	4.0E-6	1.4E-5
water	BOD	total	kg	1.9E-5	3.8E-5	1.2E-5	3.8E-5
soil	Cadmium	total	kg	4.8E-12	1.0E-11	5.8E-12	1.3E-11

Tab. 10.3 Selected LCI results and cumulative energy demands for 10 kW heat pumps including heat distribution in the house.

		Name		heat, borehole heat exchanger, brine-water heat pump 10kW, at heat radiator	heat, borehole heat exchanger, brine-water heat pump 10kW, at heat radiator	heat, air-water heat pump 10kW, at heat radiator	heat, air-water heat pump 10kW, at heat radiator
		Location		CH	RER	CH	RER
		Unit	Unit	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.16	0.53	0.20	0.71
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.50	0.40	0.69	0.56
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.16	0.06	0.23	0.08
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.78	0.79	0.00	0.01
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00	0.01	0.00	0.01
LCI results							
resource	Land occupation	total	m2a	7.2E-4	9.8E-4	9.8E-4	1.3E-3
air	Carbon dioxide, fossil	total	kg	1.3E-2	4.1E-2	1.6E-2	5.5E-2
air	NMVOC	total	kg	1.1E-5	1.7E-5	1.1E-5	2.0E-5
air	Nitrogen oxides	total	kg	4.3E-5	9.7E-5	3.0E-5	1.1E-4
air	Sulphur dioxide	total	kg	3.0E-5	1.6E-4	3.8E-5	2.3E-4
air	Particulates, < 2.5 um	total	kg	6.0E-6	1.4E-5	5.2E-6	1.6E-5
water	BOD	total	kg	2.2E-5	4.2E-5	1.5E-5	4.2E-5
soil	Cadmium	total	kg	5.6E-12	1.1E-11	6.6E-12	1.4E-11

A heat pump operating in Switzerland, i.e. supplied with the Swiss electricity mix, shows significantly lower fossil cumulative energy demand compared to a heat pump supplied with UCTE electricity. The reason for the difference is the high share of nuclear and hydro power in the Swiss electricity mix compared to average European electricity. On the other hand, the cumulative energy demand for nuclear and renewable energy sources is higher for the Swiss than for the UCTE case. The relatively high cumulative energy demand in the category “wind, solar, geothermal” for the brine/water heat pumps represents essentially the heat extraction from the ground, since wind contribution is very marginal for the Swiss electricity supply mix and photovoltaic is negligible. By contrast, the heat extraction from the ambient air for the air/water heat pump does not show up, because the heat is released back into the ambient air.

The cumulative CO_2 emissions for a heat pump operating in Switzerland without consideration of the heat distribution are between 10 g/MJ (brine/water heat pump) and 13 g/MJ (air/water heat pump). The same heat pumps operating under identical annual climatic conditions at an average location in Europe supplied by the UCTE electricity mix have cumulative CO_2 emissions between 37 g/MJ (brine/water heat pump) und 51 g/MJ (air/water heat pump). Anyway, no seasonal variations of the electricity mixes have been considered in ecoinvent, but only annual averages.

Small amounts of the refrigerant are emitted during refrigerant production, during heat pump production, during heat pump operation, and during heat pump scrapping. In case of the considered R134a heat pumps, the emissions of the refrigerant R134a are significant in relative terms for total greenhouse gas (GHG) emissions.

Fig. 10.1 shows the cumulative GHG emissions in gCO_2-equiv./MJ for 100 year time horizon (IPCC 2001). Without heat distribution, total GHG emissions add up to about 15 gCO_2-equiv./MJ for the brine/water heat pump in Switzerland and about 21 gCO_2-equiv./MJ for the air/water heat pump in Switzerland. For UCTE electricity mix, the figures are about 43 gCO_2-equiv./MJ for the brine/water heat pump and about 60 gCO_2-equiv./MJ for the air/water heat pump.

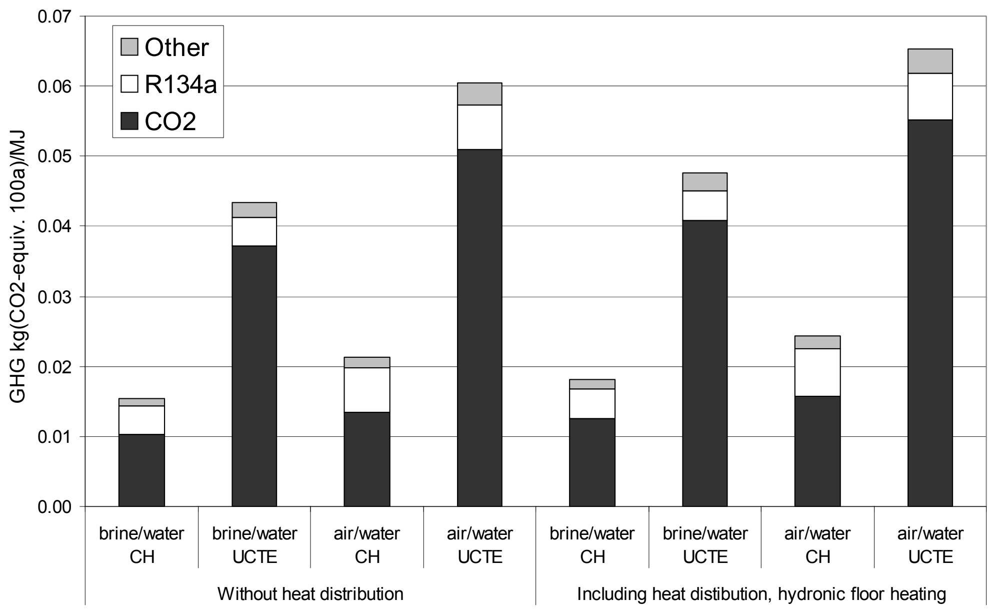

Fig. 10.1 Total greenhouse gas (GHG) emissions related to heat from heat pumps with and without heat distribution for Swiss electricity supply mix and average UCTE electricity mix.

10.4 Conclusions

Air/water and brine/water 10 kW heat pumps have been modelled for Swiss average conditions and one reference European case. Significant differences in cumulative results due to the different natural heat reservoirs and different electricity supply were estimated. For total cumulative greenhouse gas emissions from a heat pump with refrigerant R134a, the emissions of the refrigerant are relatively significant for the cumulative amounts.

10.5 References

Beyeler 2003 — Beyeler F. (2003) Medienmitteilung 10. April retrieved from: www.fws.ch/dateien/Verkaufszahlen_02.pdf.

Erb M. & P. 2001 — Erb M. and P. H. (2001) Field analysis of Swiss heat pump installations. In: EA Heat Pump Centre Newsletter, 19(1), pp., retrieved from: www.heatpumpcentre.org.

Frischknecht 1999 — Frischknecht R. (1999) Umweltrelevanz natürlicher Kältemittel; Ökobilanzen von Wärmepumpen und Kälteanlagen. Bundesamt für Energie, Bern, retrieved from: http://www.waermepumpe.ch/.

Frischknecht & Faist Emmenegger 2003 — Frischknecht R. and Faist Emmenegger M. (2003) Strommix und Stromnetz. 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, Dübendorf, CH retrieved from: www.ecoinvent.ch.

Heck 2004 — Heck T. (2004) Wärmepumpe. 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, Dübendorf, CH retrieved from: www.ecoinvent.ch.

Hess 1993 — Hess H. (1993) Personal Communication. Polydynamics Ltd., Zürich.

IPCC 2001 — IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (ed. Houghton J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A.). Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Lovvorn 2001 — Lovvorn N. C. (2001) Reliability and Lifetime of Residential Heat Pumps. In: Proceedings of Joint HPC and IPUHPC Workshop "Hands-On Experience with Heat Pumps for Buildings," 10-11 October 2001. Arnhem, The Netherlands. IEA Heat Pump Centre, Sittard, The Netherlands.

WPZ 2003 — WPZ (2003) Wärmepumpen-Testliste retrieved from: http://www.wpz.ch/.

11 Solar Collector Systems

Author: Niels Jungbluth, ESU-services

11.1 Introduction

The system model for solar collector systems describes the direct use of solar energy for warm water supply and heating with some examples. Systems for one-family houses and multiple dwellings in Switzerland are modelled. Two different types (flat plate and glass tube) of solar collectors are distinguished (see Fig. 11.1).

All solar collector systems are equipped with an additional heating system to compensate insufficient production in periods of cloudy weather. Unit process inventory data are calculated for two cases: pure solar heat and combined solar heating, for which about 40% to 75% of the heat is covered by a second source.

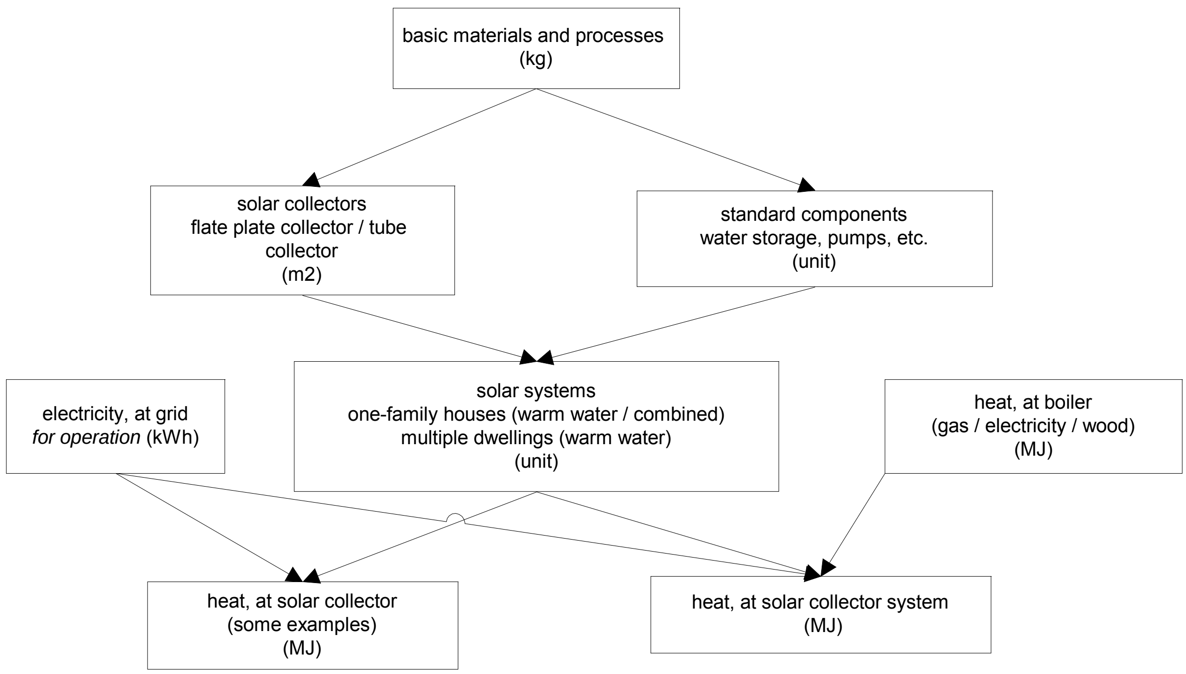

Fig. 11.1 Different sub systems investigated for solar thermal energy.

11.2 System description

All subsystems described in Fig. 11.1 are included in the system. In particular two main subsystems are distinguished for solar heating systems, namely manufacturing/dismantling and operation (Jungbluth 2003).

11.2.1 Manufacturing and dismantling

Manufacturing of solar collectors is modelled based on information from Swiss and European companies. The different solar systems comprise a field of collectors (between 4 to 12 m^2 for the one family house, 58 m^2 for the multiple dwelling), pipes including insulation, heat exchanger, pumps, storage tanks, working fluid, expansion vessel and additional heating system with gas, electricity or wood.

The collectors consist of an absorber with a selective coating, a covering (single glazing), an insulation, a casing and frame and a sealing. The main absorber material is copper (gilled absorbers). Glazing materials are glass or polycarbonate, insulation materials are mineral wool, foams or vacuum and the casing is made out of aluminium.

Inventory data comprise materials and transport services required. Energy demand and infrastructure for manufacturing is included for most components. NMVOC- and particulates-emissions during manufacturing (from coatings and welding, respectively) are included. Land use of the collectors mounted on the roof is not considered as it is on a covered surface. End of life waste treatment processes of solar collectors are included, although based on the standard assumptions used in ecoinvent due to little experience with existing equipment. For recyclable parts a cut-off approach is chosen, which allocates no environmental burdens to the solar collector systems. This approach is line with the general ecoinvent methodology.

11.2.2 Operation

Solar gains are modelled for different solar systems operated in Rapperswil, a town in the Swiss midlands. Operation includes electricity demand for circulating pumps and heat losses of the system (especially storage tanks and piping).

There are two cases for the heat supply: at collector and at system. The “at collector” case is artificial because it extrapolates the square meters of collectors needed per MJ from the specific gains of the collector operated with an auxiliary heating system. Hence, it shows the environmental burdens of the solar part of such a hybrid system and not the burdens of a system completely relying on solar energy. The case “at system” considers the auxiliary heating and it could thus be representative for a solar collector system that delivers warm water and space heating energy.

Maintenance activities are not included in the process data. Any kind of accidents or incidences in connection with the collector systems are excluded.

Electricity consumption for the additional heat supply, for circulation pumps and for the manufacturing of the equipment in Switzerland (storage tank etc.) is modelled with the Swiss supply mix, low voltage.

Transports of the system from the manufacturing site to the place of operation are considered based on information from a Swiss supplier. The lifetime of the solar thermal systems is assumed to be 25 years for all components.

The energy gain is simulated with the software program “Polysun” that comprises the entire system (including losses of piping and storage tank and the demand pattern) (Polysun 2002). The annual heat demand is assumed to be about 16 MWh for one-family houses that need heating and warm water and 170 MWh for multiple dwellings for which solar collectors would cover a part of the demand of warm water. The system that delivers only warm water for a one-family house is modelled with a heat demand of 3,7 MWh per year.

Other applications of solar thermal energy, e.g. in industry, for heating swimming pools or for drying grass, are not inventoried in the ecoinvent database.

11.2.3 Key assumptions for life cycle inventories

The full life cycle inventories with the unit process raw data for all production stages can be found in the ecoinvent database. Tab. 11.1 shows the main modelling parameters for the four solar collector systems in ecoinvent (Jungbluth 2003).

Tab. 11.1 Main modelling parameters for solar systems

			solar system with evacuated tube collector, one-family house, combined system	solar system, flat plate collector, one-family house, combined system	solar system, flat plate collector, one-family house, hot water	solar system, flat plate collector, multiple dwelling, hot water
			CH	CH	CH	CH
			a	a	a	a
energy balance	Qdem, heat use	kWh	15785.5	15730.0	3661.7	169519.0
	Qsb, solar gross yield	kWh	5901.4	5702.6	2425.0	48907.1
	Qkes, post-heat energy at boiler	kWh	11990.5	12009.5	1690.9	142911.0
	Qel, post-heat energy, electricity	kWh	0	0	0	0
	Qdif, difference to heat demand	kWh	0	0	0	2.9
	Sfi, solar coverage	%	32.8%	32.0%	58.4%	25.5%
	Qvs, storage losses	kWh	1998.4	1925.5	455.9	1508.5
	Qvz, circulation losses	kWh	0	0	0	20805
	Qvl, distribution losses	kWh	873.3	716.9	355.9	472.6
materials	heat storage	l	204	204		
	hot water tank	l	1200	1200	400	1500
	collector surface	m2	10.5	12.3	4	58.3
	slope	Grad	45°	45°	40°	30°
	inside tube installation	m	10	10	10	25
	inside tube installation	m	10	10	8	25
	heat storage liquid	l	38	40	12	170
	control unit	W	7.5	7.5	3	4
	pump power	W	50	50	40	80
	operating hours, pump	h	2300	2000	2600	2600
	life time	a	25	25	25	25
	life time yield	MJ	1420695	1415700	329553	15256710
	electricity use, pump and controlling	kWh/MJ	3.16E-3	2.90E-3	9.85E-3	3.97E-4
	sun radiation	kWh	11477	13444	4372	63722
	efficiency	%	51%	42%	55%	77%
	gross to net yield	%	113%	113%	112%	113%
	life time yield, solar	MJ	468597	455800	194166	3889943

11.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

Tab. 11.2 shows selected LCI results and the cumulative energy demand for different stages of the production chain. The data are given for the final delivery of a MJ of useful heat at collector (or solar system). The stages are: selective coating of the collector, production of the collector, production of other components for the solar collector system, operation of the solar collector, and operation of the whole system including auxiliary heating. Fig. 11.2 shows a graphical analysis of the contribution of different stages to the total.

The section between 0% and 100% in Fig. 11.2 provides the shares of different production stages for the distribution of heat, not including the auxiliary heating. The selective coating of the collector is not important for the total environmental burdens (only a small contribution of 2% is visible for Cr-VI). More important is the collector itself and the additional components of the system. Major burdens (e.g. BOD and chromium VI emissions) arise from the required metals (copper and steel) for the construction. Also the operation phase with the electricity use for pumps is significant for several results (CED, CO_2). The use of renewable solar energy during the operation phase is inventoried for the system.

Fig. 11.2 shows also the contribution from the auxiliary gas heating. The fossil energy demand and CO_2 emissions are quite higher due to the necessary gas combustion in the boiler. Cumulative results for other elementary flows per MJ delivered are smaller (dark bar goes to the left) when considering the additional heating due to the high specific burdens of material production for the solar system, e.g. land occupation and particulates. This shows that it is necessary to analyse a wide range of environmental burdens for an analysis. Only an estimation of the cumulative energy demand is not sufficient.

Tab. 11.2 Selected LCI results and the cumulative energy demand for different stages of the production chain for solar collector systems

		Name		selective coating, copper sheet, black chrome	flat plate collector, at plant	solar system, flat plate collector, one-family house, hot water	heat, at flat plate collector, one-family house, for hot water	heat, at hot water tank, solar+gas, flat plate, one-family house
		Location		RER	CH	CH	CH	CH
		Unit	Unit	pro MJ	pro MJ	pro MJ	MJ	MJ
LCIA results								0
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.5E-4	2.7E-2	8.2E-2	1.1E-1	6.5E-1
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.8E-4	7.1E-3	2.3E-2	8.4E-2	8.2E-2
	cumulative energy demand	renewable energy resources, water	MJ-Eq	5.9E-5	4.3E-3	8.8E-3	2.8E-2	2.7E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	7.2E-6	1.6E-4	4.7E-3	1.8E+0	1.2E+0
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	9.8E-6	7.3E-4	2.9E-3	3.3E-3	2.2E-3
LCI results								0
resource	Land occupation	total	m2a	2.4E-6	1.7E-4	7.5E-4	8.3E-4	5.7E-4
air	Carbon dioxide, fossil	total	kg	4.5E-5	1.9E-3	5.7E-3	7.5E-3	3.4E-2
air	NMVOC	total	kg	1.8E-8	1.4E-6	5.8E-6	7.3E-6	2.3E-5
air	Nitrogen oxides	total	kg	1.0E-7	7.3E-6	2.2E-5	2.6E-5	3.5E-5
air	Sulphur dioxide	total	kg	6.9E-7	1.3E-5	2.7E-5	3.0E-5	3.5E-5
air	Particulates, < 2.5 um	total	kg	2.0E-8	2.4E-6	7.7E-6	8.2E-6	5.8E-6
water	BOD	total	kg	4.0E-8	9.9E-6	4.5E-5	4.7E-5	3.2E-5
soil	Cadmium	total	kg	1.8E-13	2.5E-12	1.0E-11	1.5E-11	9.5E-12
Further LCI results								0
water	Chromium VI	total	kg	3.8E-9	4.4E-8	2.6E-7	2.6E-7	1.8E-7

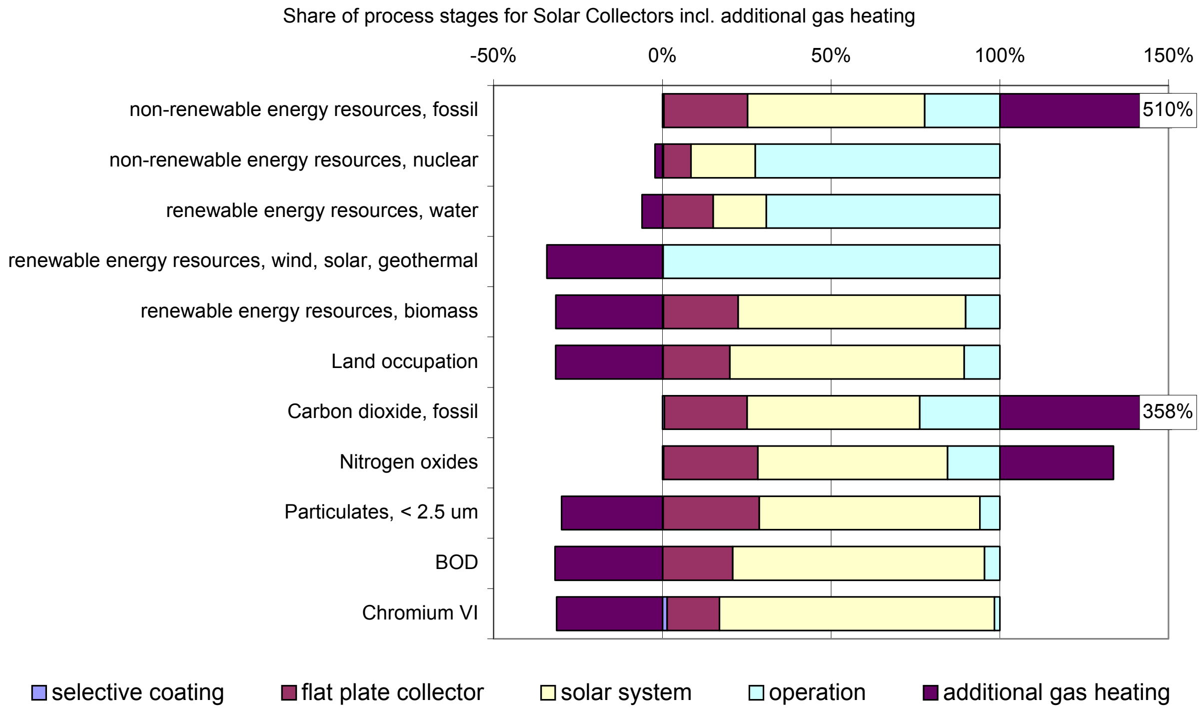

Fig. 11.2 Share of different stages of the production chain of solar heating with an auxiliary gas heating.

Fig. 11.3 shows a comparison of the cumulative elementary flows for solar collector systems (including auxiliary heating) with the corresponding solar system without an auxiliary heating (whose results are not included in the picture). Numbers below 1 indicate that the solar systems has higher flows than the reference system while a figure higher than 1 means that the inclusion of the auxiliary heating causes higher elementary flows (ratios over 10 have been cut in the figure). The solar collectors show some disadvantages in terms of land occupation, BOD emissions to water and cadmium emissions to soil. On the other hand, many flows like fossil energy demand or emissions of important air pollutants can be drastically reduced in comparison to just using a conventional heating system.

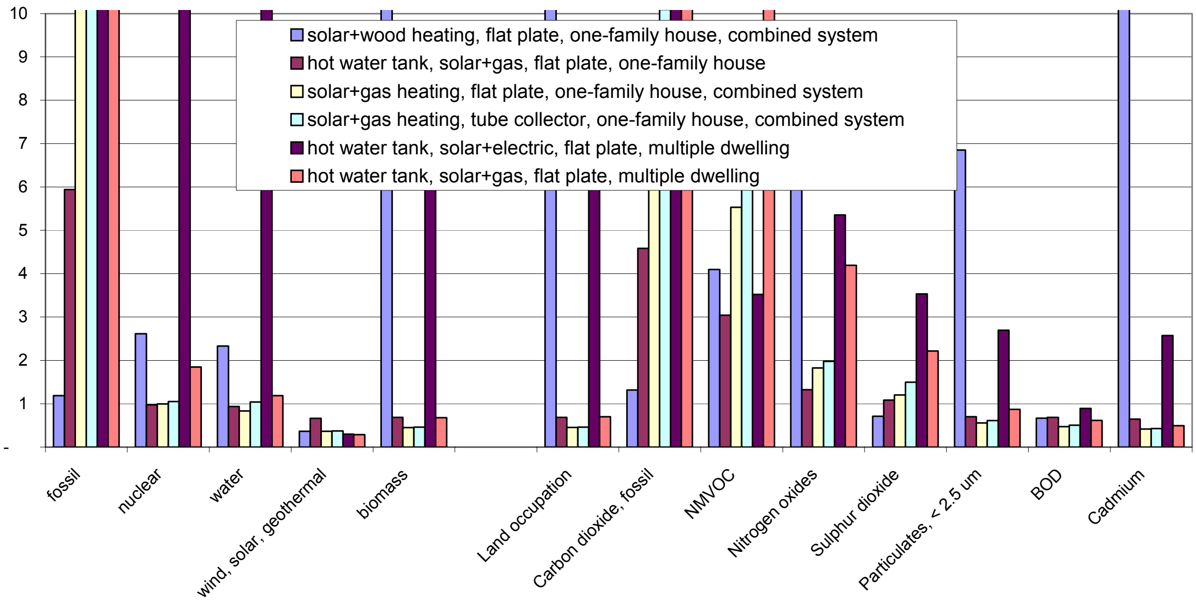

Fig. 11.3 Comparison of cumulative elementary flows for solar collector systems (including auxiliary heating) relative to the corresponding solar system without auxiliary heating

11.4 Conclusions and outlook

The inventory for solar collector systems describes certain case studies for these types of installation used in Switzerland. These examples are not representative for the market situation nor for the average installations of such systems. Thus these examples cannot be used as background data to assess right away the environmental burdens of a solar collector system. Also it is not possible to use the results directly for a general comparison with other means of house heating.

For a correct comparison of alternative heating systems for a specific application, the characteristics of the location and the proposed/possible design(s) for the solar hybrid system shall be taken into account to re-calculate the cumulative burdens. The database contains detailed inventories for different components of such solar systems, which should be sufficient to model a different system representative for a specific situation in a practical application. Besides the components, also material data and information about production processes (e.g. the selective coating of the absorber) can be found in the database. The components used and the energy balance of the system play an important role. Thus to perform an analysis of a different system design or location it is necessary to have information about the solar irradiation, the auxiliary heating and other key factors of the system.

The inventories can be assumed as a good basis for such an assessment and there are no identified major shortcomings in the inventories available. New research in this area might reinvestigate the market situation. New developments might be included in a future update.

11.5 References

Jungbluth 2003 — Jungbluth N. (2003) Sonnenkollektoranlagen. 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.

Polysun 2002 — Polysun (2002) Polysun V3.3, Simulationsprogramm für Sonnenenergieanwendungen,. Institut für Solartechnik SPF, Hochschule Rapperswil, Exertec Engineering AG, Rapperswil, Bezugsstelle: Infoenergie, Brugg.

12 Photovoltaic

Author: Niels Jungbluth, ESU-services

12.1 Introduction

The model for photovoltaic energy systems describes the production of electricity with photovoltaic small power plants newly installed in Switzerland. Twelve different, 3kWp capacity, grid-connected photovoltaic plants were studied, namely ten for current conditions and two for near future (2005-2010) conditions, for which a scenario for a future production technology has been assumed (see Tab. 12.1). The plants differ according to the cell type (mono- and polycrystalline, mc-Si and pc-Si, respectively), and the place of installation (slope roof, flat roof, and façade). Slope roof and façade systems are further distinguished according to the kind of installation (building integrated or mounted). A detailed description of the inventories can be found in (Jungbluth 2003). All inventory data are documented in the ecoinvent database.

Tab. 12.1 Overview of the 12 types of photovoltaic systems investigated. All plants have a capacity of 3 kW_p

Installation	Cell type	Panel type [1)]
Slanted roof	mc-Si	Panel
	pc-Si	Panel
	mc-Si	Laminate
	pc-Si	Laminate
	mc-Si, future	Laminate
	pc-Si, future	Laminate
Flat roof	mc-Si	Panel
	pc-Si	Panel
Facade	mc-Si	Panel
	pc-Si	Panel
	mc-Si	Laminate
	pc-Si	Laminate

1) Panel = mounted; Laminate = integrated in the roof construction.

12.2 System description

All subsystems shown in Fig. 12.1 are included in the system model. The investigated product systems include quartz reduction, silicon purification, wafer, panel and laminate production, manufacturing of converter and supporting structure. Assumed operational lifetime for all panels is 30 years. Furthermore, transports of materials, energy carriers, semi-finished products, complete power plant, and waste treatment processes for production wastes and end of life wastes are considered. Air- and waterborne process-specific pollutants are included as well. The photovoltaic system in particular is divided into unit processes for each of the shown process steps, which will be described in the next sections. Key parameters of the modelling are shown in Tab. 12.2.

12.2.1 Quartz reduction, production of metallurgical grade silicon (MG-silicon)

The production of MG-silicon is based on carbothermal reduction of silica sand using petrol coke, charcoal and wood chips as reduction agents. The consumption of reduction agents, the electricity use, the quartz input (represented by silica sand), and the emission of air- and waterborne pollutants (CO_2, SO_2 and trace elements emitted with SiO_2 dust) are included in the inventory. The main part of the production in Europe takes place in Norway, but the exact share is not known. Thus, the Norwegian electricity mix (with a high share of hydro power) has been considered for the inventory (see Tab. 12.2). By-products of the MG-silicon production process such as gases, wood spirit or acetic acid are disregarded because they are of minor interest for the economic performance of the plant. They do not bear emissions and requirements from the process nor are they allocated to the MG-silicon as a waste output.

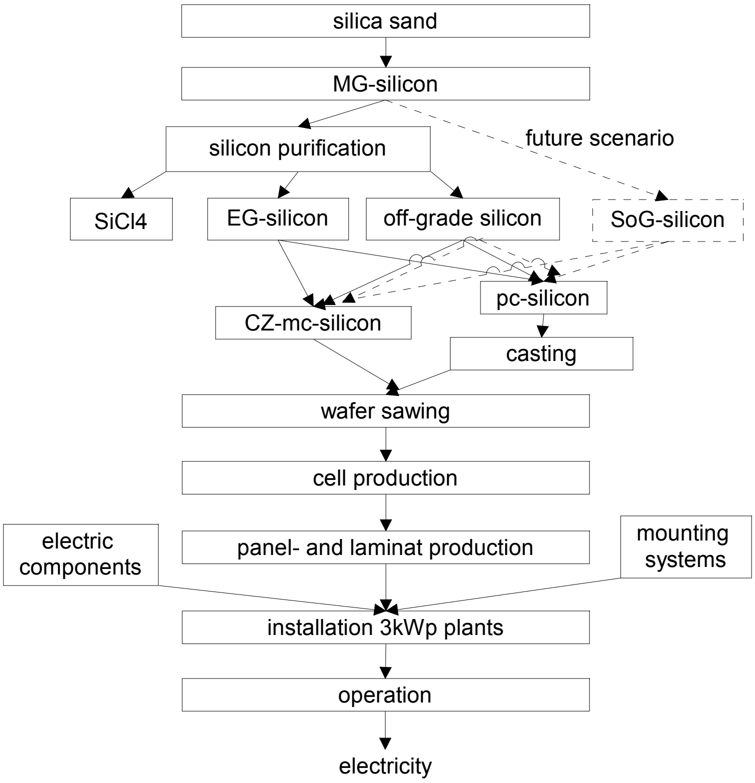

Fig. 12.1 Different sub systems investigated for photovoltaic power plants. The future scenario is shown with dotted arrows. MG-silicon: metallurgical grade, EG-silicon: electronic grade, SoG-silicon: solar grade

12.2.2 Production of electronic grade silicon (EG silicon)

MG-silicon is converted to EG-silicon (via reaction to trichlorosilane) in the Siemens process. Pieces of EG-silicon are purified in a corrosive bed. Inventory data and allocation factors are based on information available for the most important producer in Europe, which is located in Germany. Thus it cannot be regarded as representative for other technologies or production sites. Electricity consumption is assumed with the mix used at this plant, which is about 25% from hydropower and 75% from natural gas combined heat and power plant. This process provides three different products, which are used in three different economic sectors (see Fig. 12.2). The allocation of inputs and elementary flows is based on different flow specific principles. For material inputs of MG-silicon and hydrogen chloride, an allocation based on the mass of chemical elements has been chosen. The energy input is allocated based on economic parameters (prices and earnings for the different products). Thus the main part of the burdens from the process is allocated to the production of EG-silicon.

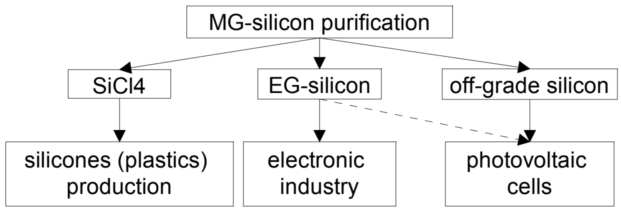

Fig. 12.2 Purification of MG-silicon delivering three different co-products

12.2.3 Production of Czochralski grade silicon (CZ-silicon)

The EG-silicon is molten and a growing crystal is slowly extracted from the melting-pot. Inventory data are based on literature information and environmental reports of one producer in Germany. The product is monocrystalline silicon. The UCTE production mix has been used to model the electricity supply. For the future scenario a reduction of the electricity consumption rate has been assumed (Tab. 12.2).

12.2.4 Production of monocrystalline wafers

The monocrystalline columns are sawn into wafers of 300 µm thickness. Process data include electricity, water and working material consumption (stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid, hard coal as proxy for graphite). Production wastes to be treated and process-specific air- and waterborne pollutants are considered based on information from literature and environmental reports. Emissions of NO_x and nitrate due to surface etching with HNO_3 are important, but data for these emissions have only been assessed from one production site. It is not known if these data are also valid for other production sites because such information was not available.

12.2.5 Production of polycrystalline wafers

EG-silicon, Off-grade silicon and SoG-silicon (solar grade) are molten and casted into reusable moulds made out of graphite. The polycrystalline columns are sawn into wafers of 300µm thickness. The process data include electricity, hard coal, water and working material consumption (stainless steel for saw-blades, argon gas, hydrofluoric and hydrochloric acid). Production wastes to be treated and process-specific air- and waterborne pollutants are considered. Emissions of NO_x and nitrate due to surface etching with HNO_3 are important. The same data as for the mc-Si wafer production have been used for these process emissions.

12.2.6 Production of monocrystalline and polycrystalline solar cells

Production of solar cells includes purification and etching of the wafers. Afterwards wafers are endowed with phosphorus and after further etching processes, front and rear contacts are printed. Process data include working material consumption (acids, oxygen, nitrogen and highly purified water), electricity consumption and production wastes. Furthermore process-specific air- and waterborne pollutants are considered, mainly hydrocarbons and acids. Cell efficiencies are estimated with data provided by several different producers for their actual products.

12.2.7 Production of monocrystalline and polycrystalline solar panels and laminates

Solar cells are embedded in layers of ethyl-vinylacetate (one each on the front and the back). The rear cover consists of a polyester, aluminium and polyvinylfluoride (Tedlar) film. A 4 mm glass poor in iron is used for the front cover. The sandwich is joint under pressure and heat, the edges are purified and the connections are insulated. A connection box is installed. The panel gets additionally an aluminium frame. Finally, panels and laminates are tested and packed. The process data include construction material (including wafer production) and energy consumption as well as the treatment of production wastes.

12.2.8 Mounting of monocrystalline and polycrystalline solar panels and laminates

Panels are mounted on top of houses and laminates are integrated into slope roofs and façades. Flat roof systems are mounted on the roof. Process data include construction materials as well as transports to the plant site.

Photovoltaic systems integrated in roofs and façades fulfil two functions, namely, electricity production and weather protection. Allocation between these two functions is made based on the economic value of and the primary energy demand for conventional wall and roofing materials and photovoltaic systems. This results in 100% allocation to electricity production.

Transports of the photovoltaic system from the manufacturing site to the place of operation include personnel transports for mounting.

12.2.9 Construction of converters and electric equipment

Process data for manufacturing the converter and of the electric equipment includes construction materials, energy requirement (for converter only), packaging materials (for converter only) and transport services.

12.2.10 Operation of photovoltaic power plants

The photovoltaic plants in operation in Switzerland show an average electricity production of 819 kWh per kW_p. For the inventory of flat and slanted-roof installations only the best 75% plants with an average production of 885 kWh/kW_p have been considered to roughly disregard the low efficient installations. An average façade-system with vertically oriented panels is calculated to produce 626 kWh per kW_p. Water consumption (for cleaning the panels once a year) is included in the inventory.

12.2.11 Dismantling of photovoltaic power plants

For the dismantling of photovoltaic power plants standard scenarios from the ecoinvent project have been taken into account. Larger metal parts of the system and silicon are recycled. The remaining parts are incinerated or landfilled.

12.2.12 Key parameters for life cycle inventories

The full life cycle inventories with the unit process raw data for all production stages can be found in the ecoinvent database (Jungbluth 2003).

Tab. 12.2 shows the key parameters of the life cycle inventory in ecoinvent Data v1.1. Main changes in comparison to older inventories are the update of the energy use in EG-silicon production, the location specific consideration of power consumption, and the inclusion of many additional process specific emissions. The material efficiency for silicon in the life cycle has been investigated for the situation in the year 2000

Tab. 12.2 Key parameter of the life cycle inventory for photovoltaic power production

	unit	mc-Si	pc-Si	mc-Si future	pc-Si future
MG-silicon production					
electricity use, NO hydro power	kWh/kg	11	11	11	11
EG-silicon production					
electricity use, DE, plant specific	kWh/kg	103	103	37	37
CZ-silicon production					
electricity use, UCTE	kWh/kg	123	-	100	-
mc-Si and pc-Si wafer					
thickness wafer	µm	300	300	300	300
sawing gap	µm	200	200	200	200
wafer area	cm^2	100	100	100	100
weight	g	6.99	6.99	6.99	6.99
cell power	W_p	1.65	1.48	1.75	1.57
cell efficiency	%	16.5%	14.8%	17.5%	15.7%
use of MG-silicon	g/Wafer	19.0	19.2	16.3	18.1
EG-silicon use per wafer	g/Wafer	11.2	11.2	9.3	9.3
process energy	kWh/Wafer	0.3	0.3	0.15	0.15
mc-Si and pc-Si cells					
process energy	kWh/cell	0.2	0.2	0.11	0.11
panel/ laminate, mc-Si/ pc-Si					
number of cells	cells/panel	112.5	112.5	112.5	112.5
panel area	cm^2	12529	12529	12529	12529
active area	cm^2	11250	11250	11250	11250
panel power	Wp	185	166	197	177
efficiency production	%	97%	97%	97%	97%
use of cells mc-Si/ pc-Si	cells/kW_p	608	677	571	637
process energy	MJ/kW_p	0.23	0.26	0.20	0.23
3kWp-plant					
panel area	$m^2/3kW_p$	18.2	20.3	17.1	19.1
operation					
yield, slope-roof	kWh/kW_p	885	885	885	885
yield, facade	kWh/kW_p	626	626		
yield, CH electricity mix	kWh/kW_p	819	819		

12.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

Tab. 12.3 shows selected LCI results and the cumulative energy demand for different stages of the production chain for polycrystalline photovoltaic power plants as one example for a modelled system. The data for all systems can be found in the ecoinvent database. The data are calculated for final delivery of 1 kWh at the plant. The cumulative energy demand for solar energy describes the radiation of solar energy to the plant.

Fig. 12.3 shows the shares of different production stages to selected cumulative results. Differences for different types of energy demands are mainly due to the consideration of location specific electricity mixes. Hydropower is for example used to a larger share in the first production stage in Norway. Nitrogen oxides and BOD are emitted in high share due to the finishing of wafer surfaces. The analysis shows that each production stage may contribute an important share to cumulative results for certain environmental flows.

Tab. 12.3 Selected LCI results and the cumulative energy demand for different stages of the production chain for photovoltaic power plants using polycrystalline silicon cells

		Name		MG-silicon, at plant	silicon, mix, for PV	silicon, pc, casted, at plant	pc-Si wafer, at plant	photovoltaic cell, pc-Si , at plant	photovoltaic panel, pc-Si, at plant	3kWp slanted-roof installation, pc-Si, panel, mounted, on roof	electricity, photovoltaic, at 3kWp slanted-roof , pc-Si, panel, mounted
		Location Unit Infrastructure	Unit	NO per kWh	RER per kWh	RER per kWh	RER per kWh	RER per kWh	RER per kWh	CH per kWh	CH kWh 0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.03	0.40	0.45	0.64	0.68	0.81	0.91	0.91
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	1.1E-3	6.3E-3	3.9E-2	9.2E-2	1.2E-1	1.5E-1	1.8E-1	1.8E-1
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.6E-2	8.0E-2	8.5E-2	9.4E-2	9.9E-2	1.1E-1	1.3E-1	1.3E-1
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	5.0E-5	1.8E-4	1.0E-3	2.3E-3	3.1E-3	3.6E-3	4.0E-3	2.4E+1
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	5.9E-3	6.1E-3	6.6E-3	1.3E-2	1.3E-2	1.6E-2	2.0E-2	2.0E-2
LCI results											
resource	Land occupation	total	m2a	7.5E-4	8.4E-4	9.1E-4	2.1E-3	2.2E-3	2.7E-3	4.0E-3	4.0E-3
air	Carbon dioxide, fossil	total	kg	2.2E-3	2.1E-2	2.4E-2	3.5E-2	3.9E-2	4.6E-2	5.3E-2	5.3E-2
air	NMVOC	total	kg	1.7E-6	1.1E-5	1.1E-5	2.3E-5	3.3E-5	4.0E-5	4.6E-5	4.6E-5
air	Nitrogen oxides	high population density	kg	2.0E-7	1.2E-5	1.4E-5	**1.4E-4**	**1.4E-4**	**1.5E-4**	**1.6E-4**	**1.6E-4**
air	Nitrogen oxides	low population density	kg	**6.4E-6**	9.0E-6	1.2E-5	2.0E-5	2.4E-5	3.1E-5	3.7E-5	3.7E-5
air	Nitrogen oxides	lower stratosphere + upper troposphere	kg	1.6E-14	2.2E-14	3.0E-14	1.1E-13	1.2E-13	1.5E-13	2.2E-13	2.2E-13
air	Nitrogen oxides	unspecified	kg	1.0E-6	4.5E-6	5.8E-6	1.9E-5	2.1E-5	3.7E-5	5.2E-5	5.2E-5
air	Nitrogen oxides	total	kg	7.6E-6	2.5E-5	3.2E-5	1.8E-4	1.9E-4	2.2E-4	2.4E-4	2.4E-4
air	Sulphur dioxide	total	kg	8.6E-6	1.8E-5	3.0E-5	6.1E-5	7.5E-5	1.1E-4	1.6E-4	1.6E-4
air	Particulates, < 2.5 um	total	kg	5.3E-7	1.5E-6	2.4E-6	7.4E-6	8.6E-6	1.3E-5	2.0E-5	2.0E-5
water	BOD	total	kg	4.9E-6	8.4E-6	1.1E-5	1.6E-4	1.6E-4	1.8E-4	2.0E-4	2.0E-4
soil	Cadmium	total	kg	9.3E-13	3.9E-12	5.7E-12	1.1E-11	1.3E-11	2.0E-11	2.7E-11	2.7E-11

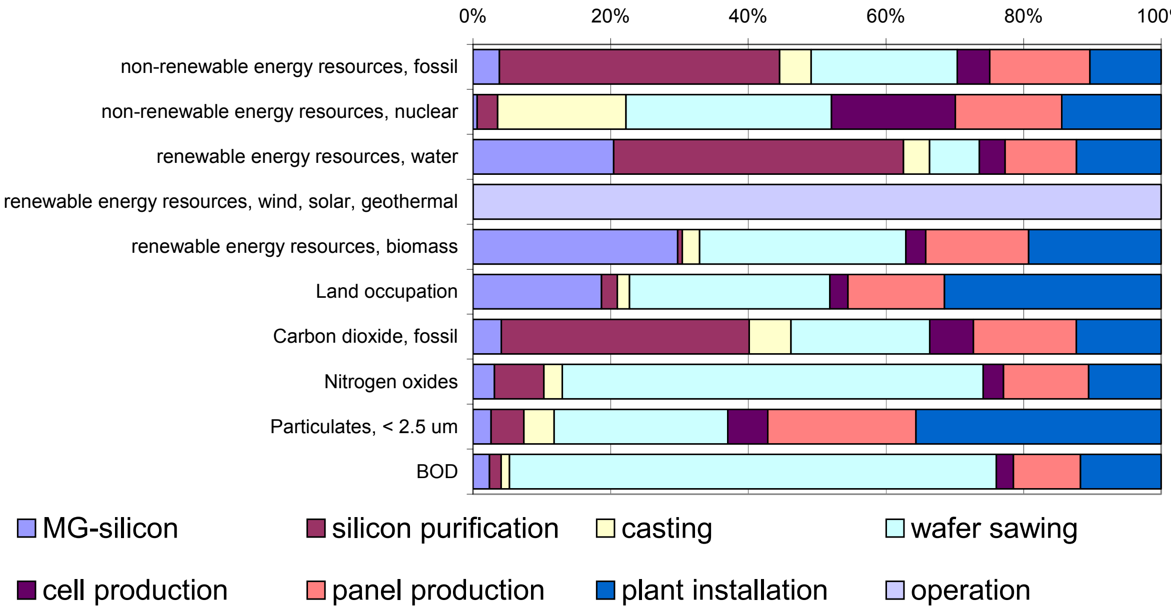

Fig. 12.3 Share of process stages for Swiss grid-connected pc-Si photovoltaic 3 kWp power plants for selected results of the inventory and an LCIA for the CED

An important yardstick for the assessment of renewable energy systems is an estimation of the energy pay back time. This describes the time until the energy uses due to the production of the plant have levelled out due to avoiding resource uses of a conventional reference system that produces the same amount of electricity. The outcome of such a comparison is influenced by the choice of the reference system on the one hand and the indicator on the other. Here we consider a modern natural gas-fired gas combined cycle power plant as the reference system (see chapter on natural gas). It is assumed that the use of photovoltaic power plants can avoid the installation of such a facility. Fig. 12.4 shows the pay-back-time for the indicators fossil, non-renewable and total energy demand. This time is between 3 and 6 years for the different PV plants. This means that the energy use for producing the photovoltaic plants is as high as the energy use for the operation of the gas power plant during 3 to 6 years. Thus, it is five to ten times shorter than the expected life time of the photovoltaic power plants. For improved future systems this time might shorten a little bit.

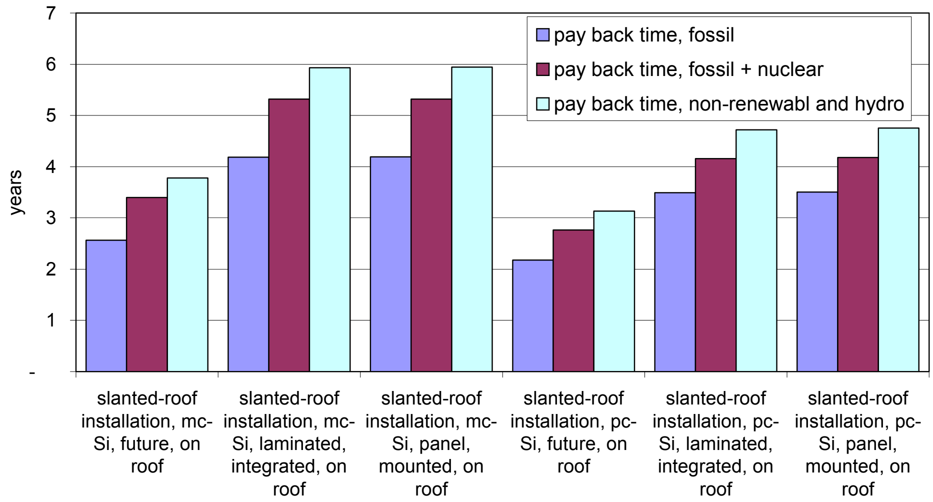

Fig. 12.4 Energy pay back time of slanted-roof photovoltaic power plants in comparison to a modern gas combined cycle power plant

Fig. 12.5 shows a comparison of selected cumulative results for different types of electricity production with mc-Si solar cells. The scenario for the future slanted roof power plant shows the lowest flows in the selected categories. Façade installations have higher impacts than flat roof or slanted roof installations due to the lower productivity. However, some pollutants might be especially important for the flat roof installations that uses other types of materials and has a higher weight. Laminates show a little bit lower flows than the panels.

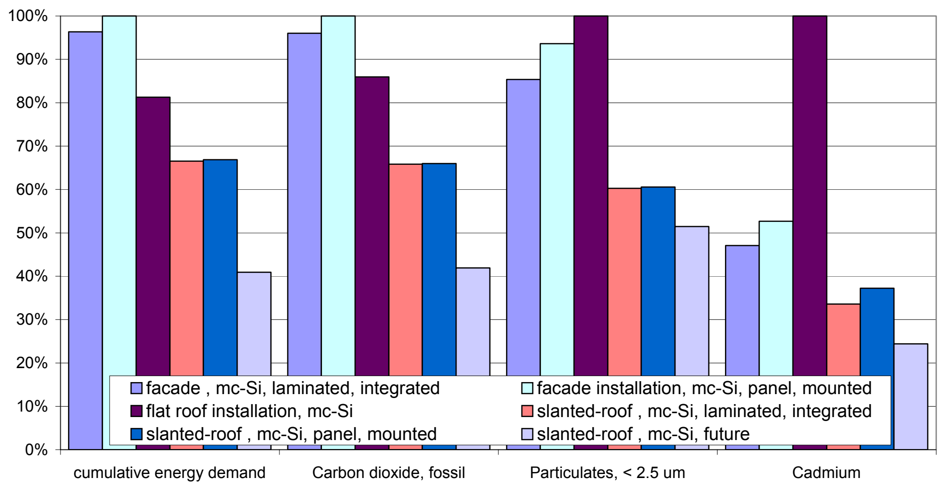

Fig. 12.5 Comparison of selected cumulative results for different types of electricity production with mc-Si solar cells

12.4 Conclusions and outlook

The life cycle inventories of photovoltaic power plants can be assumed to be representative for newly constructed plants and for the average photovoltaic mix in Switzerland in the year 2000. Differences for the situation in other countries in comparison to the data modelled for Switzerland are mainly due to different solar irradiation. It should be considered that the inventory may not be valid for wafers and panels produced outside of Europe, because production technologies and power mixes for production processes might not be the same. For the modelling of a specific power plant or power plant mixes outside of Switzerland it is advisable to consider at least the annual yield (kWh/kW_p) and if possible also the actual size of the plant in square metres.

The scenario for a future technology helps to assess the potential for improvement of different production steps in the near future (2005-2010). But, the realization of this scenario depends on the development of the market situation for electronics and photovoltaic power. The production of SoG-grade (solar grade) silicon is only possible if the supply of silicon for photovoltaic cannot be secured in the way it is today or if subsidies are granted to increase the total production.

A direct comparison of plants with pc-Si and mc-Si cells with the herewith-inventoried data has only a limited precision. For some production stages data were available only for one of the two types (e.g. NO_x emissions during wafer sawing and etching). Thus it is unclear if there are more systematic differences between the two types of cells or if the differences have to be explained by accidential variations among single production plants.

Many production processes are still under development. There are activities to establish the production of SoG-silicon, cell efficiencies are improving and the production takes place in an increasingly larger scale. Thus, future updates should verify the energy and material uses and emissions assumed in this study.

12.5 References

Jungbluth 2003 — Jungbluth N. (2003) Photovoltaik. 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.

13 Wind Power

Authors: Christian Bauer & Bastian Burger, PSI

13.1 Introduction

Due to technological improvements, wind power became in the beginning of the 1980s an economically viable alternative for electricity production. Since then, the installed capacity has been increasing, especially in California and some European countries like Denmark and Germany. In June 2003, the worldwide installed capacity was about 32 GW, whereof three quarters within the European Union.[14] In 2001 the first large European wind park has started operation in Middelgrunden, Denmark, with 20×2 MW power rate. In November 2003, the total capacity of offshore wind power plants worldwide was nearly 400 MW.[15] Installation of offshore wind power plants is expected to have high growth rates in the following years, because of the higher yields than for onshore sites.[16,17]

Since in Switzerland there are not many sites with good wind conditions, which also satisfy other criteria like landscape protection, electricity generation at wind power plants is at present marginal. At the end of year 2002, about 5.3 MW total wind capacity was installed in Switzerland, about 80% of which at the wind park Mt. Crosin, Jura, delivering about 0.01% of the total electricity production of the country.

13.2 Modelled wind power plants

The electricity production at four Swiss and two European wind turbines has been modelled in this study. The basis information comes from producers of wind power plants and electricity production data of the last ten years, supplemented with own assumptions and extrapolations in case of insufficient data. The datasets for electricity produced at the modelled wind power plants are listed in Tab. 13.1.

Tab. 13.1 Electricity, at modelled wind turbines

Location	Dataset
Switzerland	electricity, at wind power plant Simplon 30kW
	electricity, at wind power plant Grenchenberg 150kW
	electricity, at wind power plant 600kW
	electricity, at wind power plant 800kW
	electricity, at wind power plant
Europe	electricity, at wind power plant 800kW
	electricity, at wind power plant 2MW, offshore
	electricity, at wind power plant

The 800 kW wind turbine has been considered for Mont Crosin specific conditions as well as for average European conditions onshore. The 2 MW offshore unit represents one machine installed in the wind park Middelgrunden. Two average wind electricity production mixes have been modelled

[14] http://www.igwindkraft.at/aktuell/h_zahlen.htm, information retrieved in September 2003.

[15] http://home.planet.nl/%7Ewindsh/offshore.html, information retrieved in October 2003.

[16] http://www.ewea.org/documents/WIND_CAP_JUNE03.pdf, information retrieved in September 2003.

[17] http://www.windpower.org/de/pictures/offshore.htm, information retrieved in September 2003.

considering the shares of the relative contribution of the different datasets to total electricity from wind power around year 2000 in Switzerland and Europe.

13.3 System description

13.3.1 System boundaries

Fig. 13.1 shows a schematic description of the chain for electricity production at wind power plants. The construction of fixed and moving parts has been separately modelled.

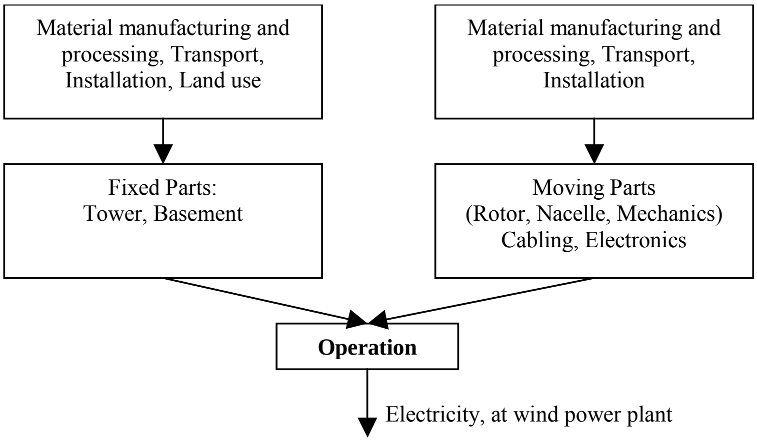

Fig. 13.1 Model of wind energy chain (schematic figure)

The dataset for fixed parts accounts for different construction materials – mainly concrete for the basement and steel for the tower –, their processing, and their transport to the manufacturing company and from this to the location of installation. Land use for the basement and energy requirements for tower installation are included as well. The moving parts are composed of the rotor, made of glass fibre reinforced plastic and small amounts of steel, and the nacelle, whose components are mainly made of different types of steel and plastics and small amounts of aluminium and copper. The copper cables, connecting the generator to the electricity grid, and various electronic components are also accounted for in the moving parts, because they are assumed to have the same lifetime. Similarly to the fixed parts, processing, transport of materials to the manufacturer and from it to the location of final installation, as well as the energy requirement for assembling and final installation are accounted for. During operation, some lubricating oil must be refilled.

13.3.2 Capacity factor

The capacity factor depends on the wind conditions and the characteristics of the wind turbine. For Switzerland, the capacity factors of the single modelled wind power plants are calculated using electricity production statistics of recent years in order to have a sort of average values. The resulting capacity factors are 8.5% for the 30 kW plant, 10.5% for the 150 kW plant, and 14% for both the 600 kW and 800 kW plant (Meteotest 2002, Juvent 2003). The capacity factor assumed for the European 800 kW onshore plant is 20%, calculated using the total installed capacity and corresponding electricity production at European wind power plants in year 2002.[18] As the operation of the offshore wind park Middelgrunden is relatively short, it cannot be predicted, whether the average annual electricity production data reflect average production over the whole lifetime. In year

[18] http://www.greenpeace.org/deutschland/?page=/deutschland/fakten/energie/wind/windparks-an-land, http://www.vistaverde.de/news/Wirtschaft/0303/03_windkraft.htm , http://www.wind-energie.de/zeitschrift/neue-energie/jahr-2002/inhalte/ne-1102/nov_1.htm, http://www.energetik-leipzig.de/Ausg_1_03-2.html, retrieved in July 2003.

2002, the 20 turbines produced about 104 GWh, in year 2003 nearly 90 GWh, which gives an average capacity factor of 27.4%.[19] For this study, a capacity factor of 30% is assumed for a generic 2 MW offshore turbines installed in Northern Europe, since average wind speed will be probably higher with increasing distance to the shore.

13.3.3 Lifetime

In order to calculate the environmental burdens per kWh electricity, all requirements must be normalised to the total electricity production over the lifetime of the wind power plant. For the onshore wind power plants, the lifetime of 40 years is assumed for the fixed parts, and 20 years for the moving parts. For all components of the 2 MW offshore plant, lifetime is assumed 20 years.

13.3.4 Material and energy requirements

Tab. 13.2 through Tab. 13.4 give an overview of the materials used for the different parts of the 800 kW wind turbine, Tab. 13.5 through Tab. 13.7 show the material requirements for the 2 MW turbine, as examples. The 800 kW turbine has 50 m high tower and 50 m diameter three blade rotor. The 2 MW turbine has 60 m high tower and 76 m diameter three blade rotor. Data for all other modelled wind power plants are available in the German report or directly retrievable from the ecoinvent database. The amounts are based on information from manufacturing companies, as specified in the notes to the tables. For some parts as the nacelle, only the lumped mass was available. Therefore, their estimated composition is affected by a relatively high uncertainty.

Tab. 13.2 Material use for the fixed parts of the 800 kW wind turbine

Part	Material	Requirements
Tower	Steel, low alloyed	69375 kg [a]
	Epoxy resine	360 kg [b]
Basement	Concrete	102 m^3 [c]
	Reinforcing steel	14000 kg

a Mass of tower: 60300 kg (Nordex 2001), additionally 15% for internals, plus 30 kg for welding (as soldering metal).

b 0.25 kg paint per m^2 surface and coat (Hagedorn 1991); 2 coats (Nordex 2001).

c 4500 kg concrete/m height, 280 kg reinforcing steel/m height (Steinemann D., 29.11.2001, ABB Energie Services Switzerland), density of concrete: 2200 kg/m^3.

[19] http://www.middelgrund.com/ (18.6.2004).

Tab. 13.3 Material use for the moving parts of the 800 kW wind turbine

Part		Material	Mass [kg]
Rotor	Blades	Glass fibre reinforced plastics	8400 [a]
	Extender	Chromium steel	3100
	Hub	Cast iron	3200
Nacelle			
Mechanic parts	Shaft	Steel, low alloyed	3100
	Main bearing	Cast iron	251 [a,b]
		Chromium steel	251
	Gearbox [c]	Cast iron	2200
		Chromium steel	2200
		Rubber	100
	Generator	Cast iron	828 [d]
		Chromium steel	2173
		Aluminium 0% recycled	207
		Copper	242
	Brake	Chromium steel	150 [e]
Casing	Frame	Chromium steel	5652 [f]
	Cover	Glass fibre reinforced plastics	1261 [g]
Yaw system	Ball bearing	Steel, low alloyed	585
	Drive	Chromium steel	300 [h]
	Brake	Chromium steel	200
Hydraulic system		Chromium steel	500
		Lubricant	58.8

a Masses from (Nordex 2001).
b Own estimation of shares of materials 50% cast iron and 50% chromium steel, materials from (Nordex 2001).
c Rubber estimated. Other materials from (Nordex 2001), assuming 50% weight for each.
d Mass of Generator from (Nordex 2001).
e Own assumption for mass and material.
f Total mass of nacelle from (Nordex 2001).
g 0.5% of total weight (incl. basement) of the turbine, (Communication with M.Lenzen, 17.6.02).
h Own assumption for mass and material.

Tab. 13.4 Material use for the connection between the generator of the 800 kW wind turbine to the electricity grid

Part		Material	Masses [kg]
Connection to grid	Material	Copper	1217
		HDPE	594
		PP	20
		PVC	428

Tab. 13.5 Material use for the fixed parts of the 2 MW wind turbine.

Part	Material	Requirements
Tower	Steel, low alloyed	113210 kg [a]
	Epoxy resine	547 kg [b]
Basement	Concrete	873 m^3 [c]
	Reinforcing steel	80000 kg

a Mass of tower: 98400 kg (Bonus 2002), additionally 15% for internals, plus 50 kg for welding (as soldering metal).
b 0.25 kg paint per m^2 surface and coat (Hagedorn 1991).
c Mass of basement: 200 t (Bonus 2002); share of concrete and reinforcing steel from (Schleisner 1999).

Tab. 13.6 Material use for the moving parts of the 2 MW wind turbine.

Part		Material	Mass [kg]
Rotor	Blades	Glass fibre reinforced plastics	29714 [a]
	Extender	Chromium steel	10966
	Hub	Cast iron	11320
Nacelle [b]			
Mechanic parts	Shaft	Steel, low alloyed	12661
	Main bearing	Cast iron	10025
		Chromium steel	10025
	Gearbox	Cast iron	9139
		Chromium steel	9139
		Rubber	100
	Generator [c]	Cast iron	3382
		Chromium steel	8877
		Aluminium 0% recycled	845
		Copper	986
	Brake	Chromium steel	613
Casing	Frame	Chromium steel	16940
	Cover	Glass fibre reinforced plastics	11224
Yaw system	Ball bearing	Steel, low alloyed	2389
	Drive	Chromium steel	1225
	Brake	Chromium steel	816
Hydraulic system		Chromium steel	2042
		Lubricant	150 [d]

a Total mass of rotor: 52 t (Bonus 2002); the shares of single materials assumed same as for the 800 kW turbine.
b Total mass of nacelle: 82.5 t (Bonus 2002); the shares of single materials assumed same as for the 800 kW turbine.
c Same share of materials assumed as for 30 kW turbine.
d Own estimation.

Tab. 13.7 Material use for the connection between the generator of 2 MW wind turbine to the electricity grid.

Part		Material	Masses [kg]
Connection to grid	Material	Copper	3900
		Lead	7575
		Steel, low alloyed	8766 [a]
		PVC	3500 [b]

a Used for steel in (Schleisner 1999).
b Used for PEX in (Schleisner 1999).

Tab. 13.8 shows an overview of the considered processing for the construction materials. Additionally to these processes, which include most of the total energy requirements for the infrastructure of the wind power plants, also the energy requirements for final assembling have been roughly estimated.

Tab. 13.8 Material processing for the construction of wind turbines

Material	Processing
Copper	Copper, wire drawing
Aluminium	Aluminium, sheet rolling
Chromium steel	Chromium steel, sheet rolling
Cast iron	Steel, section bar rolling
Steel, low alloyed	Steel, sheet rolling

13.3.5 Transport

The standard distances in Europe and Switzerland defined in the general ecoinvent guidelines are used for the transport of the construction materials to the manufacturer and wastes to waste treatment and deposition.

13.3.6 Waste treatment and disposal

At the end of life of the wind plant, all metals except of the steel used for reinforcing bars are assumed to be recycled, including those used for electronics, and plastics will be delivered to municipial waste incineration. A possible classification as waste of the reinforced concrete of the basement, which remains in ground or at sea bottom after the end of operation, is not taken into account. Due to lack of a specific dataset for waste disposal, the material of the blades is assumed to be burned in municipial waste incinerators as 65% glass and 35% plastics.

13.4 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

13.4.1 Selected Results

Tab. 13.9 shows selected cumulative LCI results and the cumulative energy demand for electricity generation at the 800 kW onshore and the 2 MW offshore wind power plants. Results for other datasets and mixes are available in the German report or directly retrievable from the ecoinvent database.

Tab. 13.9 Selected LCI results and cumulative energy demand for electricity generation at the wind power plants *2 MW, Offshore*, and *800 kW, Onshore, RER/CH*.

		Name		electricity, at wind power plant 2MW, offshore	electricity, at wind power plant 800kW	electricity, at wind power plant 800kW
		Location		OCE	RER	CH
		Unit	Unit	kWh	kWh	kWh
		Infrastructure		0	0	0
LCIA results						
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.64E-01	1.39E-01	1.98E-01
	cumulative energy demand	non-renewable energy resources,	MJ-Eq	4.17E-02	3.68E-02	5.27E-02
	cumulative energy demand	renewable energy resources, water	MJ-Eq	9.99E-03	8.85E-03	1.42E-02
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.44E+01	1.44E+01	1.44E+01
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.21E-03	1.05E-03	1.50E-03
LCI results						
resource	Land occupation	total	m2a	4.96E-04	1.18E-03	1.70E-03
air	Carbon dioxide, fossil	total	kg	1.23E-02	9.56E-03	1.36E-02
air	NMVOC	total	kg	1.14E-05	8.50E-06	1.21E-05
air	Nitrogen oxides	total	kg	5.64E-05	3.86E-05	5.51E-05
air	Sulphur dioxide	total	kg	4.47E-05	3.83E-05	5.45E-05
air	Particulates, < 2.5 um	total	kg	1.54E-05	1.17E-05	1.68E-05
water	BOD	total	kg	7.35E-05	3.79E-05	5.40E-05
soil	Cadmium	total	kg	8.20E-12	5.61E-12	7.33E-12
Further LCI results						
resource	Iron, 46% in ore, 25% in crude ore, in	in ground	kg	2.33E-3	1.95E-3	2.80E-3
resource	Copper, total	in ground	kg	3.83E-5	3.81E-5	5.45E-5
resource	Nickel, total	in ground	kg	3.57E-4	3.71E-4	5.31E-4
air	Particulates, > 2.5 um, and < 10um	total	kg	3.90E-5	2.06E-5	2.98E-5
air	Particulates, > 10 um	total	kg	4.47E-5	2.27E-5	3.27E-5

13.4.2 Analysis

Fig. 13.2 shows some selected air emissions associated to electricity production at the analysed wind turbines. In general, a comparison of the cumulative results of environmental burdens from the modelled onshore wind power plants shows decreasing values with increasing capacity. There are two main reasons for this fact. First, there is a scale down effect for the ratio of the masses to energy produced. Second, the actual capacity factor of the 30 kW plant is the smallest, and the one of the 150 kW plant is also smaller than the one of the 600 kW and 800 kW plants, which amplifies the scale down effect.

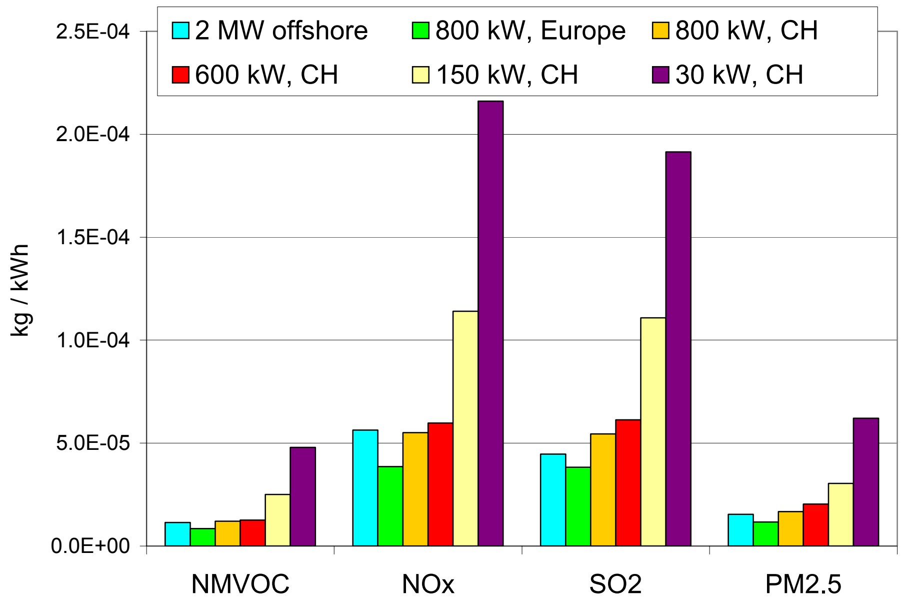

Fig. 13.2 Selected air emissions from electricity production at modelled wind turbines.

Compared to the Swiss 800 kW plant, the environmental performance of the electricity produced at the European 800 kW plant is better. Most elementary flows from the European plant are about 70% of the flows from the Swiss 800 kW plant, which basically reflects the difference in the assumed capacity factors of 20% vs. 14%. This means that the different mixes, used for electricity supplies, and different transport distances do not have important influence on the cumulative inventory results.

The comparison between electricity production at the European 800 kW onshore plant and at the 2 MW offshore plant is not straightforward. Most elementary flows are slightly higher for the 2 MW offshore plant. The reason is that the specific (per kWh electricity) requirements of concrete and reinforcing steel for the basement of the offshore plant are higher than for onshore units. Moreover, the lifetime assumed for the basement of the offshore plant is 20 years, whereas for the onshore plant it is 40 years. Additionally, the installation of the plant at sea is more complex than the onshore installation. In some cases, for example the emission of NO_x, these facts may even lead to clearly higher emissions from the electricity produced at the 2 MW offshore plant than from the electricity produced at the average European 800 kW onshore plant, as shown in Fig. 13.2.

In general, the major part of the criteria pollutants are mostly emitted during the production of the construction materials. Material processing is playing a minor role. Transport processes, final assembling and installation, and waste disposal are nearly irrelevant for most elementary flows for the onshore plants. However, this is not true for cadmium emissions, which are mostly originating in abrasion of lorry tires, for which the contribution from transport prevails. On the other hand, the installation work contributes meaningfully for the offshore plant.

Total CO_2 emissions are shown in Fig. 13.3. Material maufacturing, material processing, installation, transport, and waste disposal include the contributions from both fixed and moving parts. Operation includes all associated burdens (e.g. disposal of used lubricant).

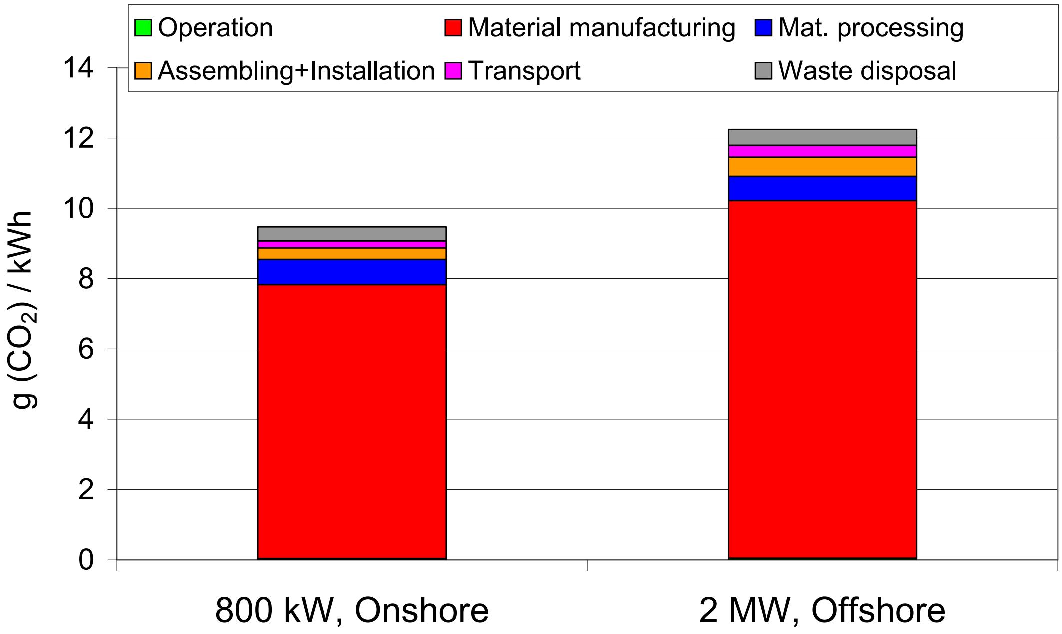

Fig. 13.3 CO_2-Emissions from electricity production at 800 kW onshore and 2 MW offshore wind turbines for average European conditions.

Concerning total greenhouse gas emissions, an analysis for the European wind turbines shows that more than 90% of the emitted greenhouse gases (in CO_2-equivalents for 100 a GWPs following (IPCC 2001)) is fossil CO_2. For the 800 kW plant, about 81% of CO_2 emissions originates from the production of materials (25% chromium steel, 25% glass fibre reinforced plastic, 18% steel low alloyed, 5% concrete, and 3% reinforcing steel); about 7% of CO_2 emissions is related to material processing, 4% to waste disposal, and the rest to transports, final assembling and installation.

For the 2 MW offshore plant, about 83% of CO_2 emissions are coming from the production of materials (18% chromium steel, 22% glass fibre reinforced plastic, 13% steel low alloyed, 17% concrete, and 6% reinforcing steel); about 6% of CO_2 emissions are related to material processing, 4% to waste disposal, 3% to transports, and the rest to final assembling and installation.

Further analysis can be found in the German report (Burger & Bauer 2004).

13.5 Conclusions and outlook

The differences for environmental burdens depend upon the capacity factor of the plants, the lifetime of the infrastructure, and the power rate. The higher these factors, the less environmental burdens are determined for onshore turbines. With respect to the scaling down effect ofincreased rated power only, the modelled 2 MW offshore plant is an exception. Although a comparison between the modelled 2 MW offshore turbine and the European 800 kW onshore plant shows that the environmental performance of the onshore turbine is better, this should not indicate an environmental advantage of onshore plants in principle, as burdens highly depend on site-specific factors, e.g. wind speed, depth of the sea, and distance from coast.

It must be mentioned that some environmental burdens have not been addressed in this LCA study. Depending on the location of the plants, aesthetic effects on the landscape or negative effect on birds may occur. These factors, which also include subjective elements, were out of scope for the ecoinvent 2000 project.

A more location-specific modelling of electricity production at European wind power plants would require detailed data on wind statistics over several years. This, together with country-specific data on capacity distribution would allow a more realistic description of country-specific wind energy mixes. Furthermore, due to the trend to increase the construction of higher capacity turbines, electricity production at onshore plants with capacity between 1 MW and 3 MW should be also modelled in the future. Taking into account the probably rising importance of offshore wind power plants, they should be modelled more accurately as soon as reliable information from cumulative years of operation will be available. A simple extrapolation of the results of the modelled offshore plants to other sites does not seem to be very reasonable, since different wind conditions as well as increased depth and distance to the shore would probably imply meaningful differences in material requirements for the foundation and the connection to the grid.

For further studies on wind power plants, it would be desirable to have more reliable data from the industry concerning the components of the nacelle, which could only be roughly extrapolated in this study.

13.6 References

ABB 1991 — Brunk F. (1991) Information from ABB for the first edition of Ökoinventare.

Bonus 2002 — Stiesdal H. (2001) Middelgrunden Offshore, A newsletter for customers and business associates, Bonus energy A/S. General technical description, Technical specification, Drawings and design, Bonus 2 MW offshore. Isager Bogtryt/Offset, Svendborg, Denmark. Retrieved from: www.bonus.dk.

Burger & Bauer 2004 — Burger B. and Bauer C. (2004) Windkraft. 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.

Hagedorn 1991 — Hagedorn G., Ilmberger F. (1991) Cumulated Energy Demand for the production of wind turbines. Forschungsstelle für Energiewirtschaft, Munich.

IPCC 2001 — IPCC (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (ed. Houghton J. T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Juvent 2003 — Website of JUVENT SA http://www.juvent.ch/about.htm, retrieved in July 2003.

Meteotest 2002 — Information from Swiss wind power plants http://stratus.meteotest.ch/mme/a_turbinenbeschrieb.asp?lang=d, retrieved in July 2003.

Nordex 2001 — Technical characterisation: Nordex N50-800 (2001). www.nordex-online.com

Schleisner 1999 — Schleisner L. (1999) Life cycle assessment of a wind farm and related externalities. Riso national Laboratory, Roskilde, Denmark.

14 Combined Heat & Power (CHP)

Author: Thomas Heck, PSI

14.1 Introduction

Several types of small combined heat and power (CHP) plants are described. For a reference plant operating in Switzerland (natural gas 160 kW_e) a detailed inventory has been established already in the previous version of ecoinvent of energy systems (1996). The data of this reference plant have been updated only to some extent. Additionally, six other natural gas CHP plants representing different technologies and different capacity classes from 2 to 1000 kW_e are included now. A 200 kW_e diesel CHP plant is modelled as well. Wood CHP plants are not described here but in the wood energy chapter (Bauer 2003).

Many basic data have been supplied by manufacturers, planners and operators. Some values like the requirements for production of plant components had to be estimated from prices and energy intensities. The materials, energy and transport requirements for manufacturing and the pollutants emitted during operation are inventoried and allocated to the products electricity and heat. Allocation is a decisive issue for the description of combined heat and power production and its choice may depend on single application or motivations of the analyst. Therefore, several variants of allocation are offered in the database for each CHP plant.

For the first time, quantitative estimates of uncertainties for all input data are included. The uncertainty factors, provided in the database as well, are the basis for the calculation of uncertainties of the cumulative results. In this short report, the uncertainties of the input data are not discussed.

Here, only a short overview is provided. For further details, the reader may refer to the full report (Heck 2004).

14.2 System description

Fig. 14.1 shows the modelled combined heat and power plants. The lambda1 motor implies a three-way catalytic converter. The lean burn CHP plants are described without catalysts. For the diesel CHP, an SCR (Selective Catalytic Reduction) catalyst and an oxidation catalyst have been considered.

The requirements for infrastructure of CHP components have been considered in detail. The basis for the modelling of the infrastructure is a 160 kW_e natural gas CHP plant operating in Basel Jakobsberg, Switzerland. Additionally, data on new CHP plants from manufacturers have been used. All datasets refer to CHP plants available at the Swiss market around year 2000 except the datasets for the reference plant Jakobsberg.

Tab. 5.4 lists the datasets available in the ecoinvent database for electricity at combined heat and power plants. Corresponding to each electricity dataset, a dataset for the heat production is provided as well. Electricity production is given in kWh, heat production in MJ. For most of the datasets it was assumed that the CHP plant is operating in Switzerland (CH). A dataset for a 1 MW_e natural gas plant located in Europe is included as well.

For modelling it has been assumed that the small CHP plants are connected to the low pressure distribution network, which has been modelled for Switzerland only (Faist Emmenegger et al. 2004). In the case of the reference European 1 MW_e CHP, the high pressure dataset has been used for natural gas supply; however, the methane emissions have been adjusted to those of the Swiss low pressure distribution in order to consider approximately the losses in European low pressure networks.

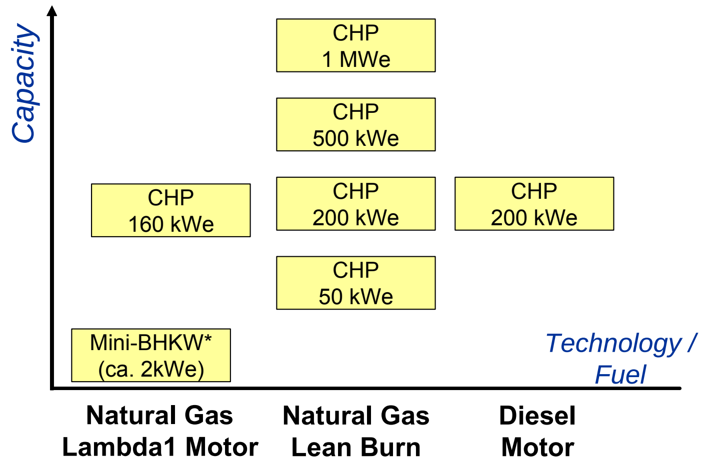

Fig. 14.1 Overview of the modelled combined heat and power plant according to technology/fuel and capacity. *) BHKW means "Blockheizkraftwerk".

Tab. 14.1 Ecoinvent datasets for electricity (unit kWh) at small combined heat and power plants. All plants are natural gas plants except the diesel plant.

Name	Allocation	Country/ Region
electricity, at cogen 50kWe lean burn	energy	CH
	exergy	
	heat	
electricity, at cogen 160kWe lambda=1, allocation	electricity	CH
	energy	
	exergy	
	heat	
	price	
electricity, at cogen 200kWe lean burn, allocation	energy	CH
	exergy	
	heat	
electricity, at cogen 500kWe lean burn, allocation	energy	CH
	exergy	
	heat	
electricity, at cogen 1MWe lean burn, allocation	energy	CH
		RER
	exergy	CH
		RER
	heat	CH
		RER
electricity, at Mini-BHKW, allocation	energy	CH
	exergy	
	heat	
electricity, at cogen 160kWe Jakobsberg, allocation	electricity	CH
	energy	
	exergy	
	heat	
	price	
electricity, at cogen 200kWe diesel SCR, allocation	energy	CH
	exergy	
	heat	

Tab. 14.2 shows the electric and thermal efficiencies for the modelled combined heat and power plants. The estimates are based on different manufacturer data (Ecopower 2001; IWK 2002; Jenbacher 2002; MENAG 2002) and literature (ASUE 2001; Eicher & Rigassi 2002; EUROMOT 2002).

Tab. 14.2 Key parameters for the modelled combined heat and power plants: efficiencies.

Type	Fuel	Class	Assumed efficiencies	
			electric	thermal
		kW_e	%	%
Mini-BHKW (lamdba1 motor)	natural gas	2	25	65
Lambda1 motor reference plant Basel Jakobsberg	natural gas	160	27	49
Lambda1 motor	natural gas	160	32	55
Lean burn motor	natural gas	50	30	54
Lean burn motor	natural gas	200	33	52
Lean burn motor	natural gas	500	36	46
Lean burn motor	natural gas	1000	38	44
Diesel motor	diesel	200	39	43

Tab. 14.3 shows essential emission factors for different types of combined heat and power plants according to Swiss conditions. The factors per MJ refer to the lower heating value of the fuel. The emission factors have been estimated based on different references (ASUE 2001; Berdowski et al. 2002; BUWAL 2001a; b; CEIDARS 2001; Ecopower 2002; EUROMOT 2002; ExternE 1999; Gantner et al. 1999; Hupperich & Schiffgens 1994; IIASA 2002; Kühnis & Eicher 1993; Lorenz 2002; MENAG 2002; MENAG Service 2002; Schmieder 2002; Ulli 2002; Viessmann 2002; WKK-Fachverband 2001; 2002).

Tab. 14.3 Key parameters for the modelled combined heat and power plants: emission factors in kg/MJ fuel burned.

Emission species	Natural gas CHP, 50-1000 kW_e, lean burn motor, no catalyst	Natural gas CHP, 160 kW_e, lambda1 motor, three-way catalyst	Natural gas CHP, Mini-BHKW, 2-5 kW_e, lambda1 motor, three-way catalyst	Diesel CHP, 200 kW_e, SCR and oxidation catalysts
Nitrogen oxides	7.00E-05	1.50E-05	2.20E-05	7.00E-05
Carbon monoxide	1.60E-04	4.80E-05	1.28E-04	1.50E-04
Carbon dioxide	5.60E-02	5.60E-02	5.60E-02	7.37E-02
Methane	8.00E-05	2.30E-05	4.30E-05	1.20E-05
NMVOC (non-methane volatile organic compounds)	1.00E-05	2.00E-06	5.00E-06	5.00E-05
Sulfur dioxide	5.50E-07	5.50E-07	5.50E-07	5.00E-05
Dinitrogen monoxide	5.00E-06	2.50E-06	2.50E-06	5.00E-06
Particulates, < 2.5 um	1.50E-07	1.50E-07	1.50E-07	1.00E-06
Ammonia				1.00E-06

The reference plant Jakobsberg operating in Basel, Switzerland, has a heat pump and two oil boilers for supplementary heat production. The heat is distributed through a local distribution network into the buildings. The heat supply of the reference plant Jakobsberg was modelled for the different steps based on operator information (Eicher+Pauli 2002): The datasets "heat, at cogen 160kWe Jakobsberg" describe the heat directly from the CHP plant. (The dataset name is always supplemented by the allocation method.) In "heat, at module cogen 160kWe Jakobsberg", the heat from the heat pump is added. Contributions from the CHP plant, from the heat pump, and from the oil boilers reflecting the average annual operation of the components are combined in the datasets “heat, at system cogen 160kWe Jakobsberg”. The datasets “heat, at local distribution cogen 160kWe Jakobsberg” describe the heat after distribution through the local distribution network.

The allocation of the common burdens to the products heat and electricity is important for the balance of combined heat and power production. For all CHP plants in the database, three methods of allocation are provided: allocation exergy, allocation energy, and allocation heat. The user is free to choose the allocation appropriate for the intended application. For the reference plant Jakobsberg and for the new 160 kW_e natural gas lambda1 CHP, five methods of allocation are considered: exergy, energy, heat, electricity, and price. Fig. 14.2 illustrates the allocation factors for the five different allocation methods. The figure refers to data of the reference plant Jakobsberg, but the distribution is essentially similar for the other plants considered. In case of energy allocation, the burdens are distributed according to the energy output of heat and electricity. In case of exergy allocation, electricity and heat are weighted with their exergy content. This results in a lower weight for the heat output. In case of heat allocation, all common burdens are allocated to the heat output. Conversely, allocation electricity allocates all common burdens to the electricity output. Allocation price describes an economic allocation according to the market prices of heat and electricity in the year 2002.

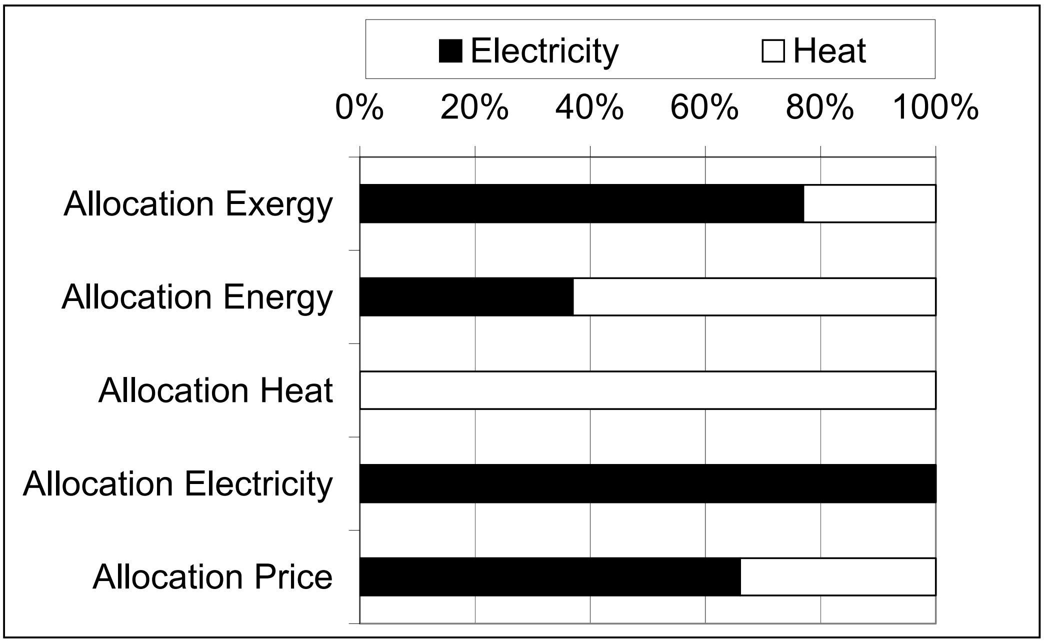

Fig. 14.2 Allocation of burdens to electricity and heat for different allocation methods. The data refers to the reference plant Basel Jakobsberg (operating 160kW_e natural gas CHP with lamdba1 motor).

14.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2.

14.3.1 Selected results

The following tables show selected LCI results and cumulative energy demands for electricity and heat production at combined heat and power plants. The results depend significantly on the chosen allocation method.

Tab. 14.4 Selected LCI results and cumulative energy demands for electricity at combined heat and power plants, allocation exergy.

		Name		electricity, at Mini-BHKW, allocation exergy	electricity, at cogen 50kWe lean burn, allocation exergy	electricity, at cogen 160kWe Jakobsberg , allocation exergy	electricity, at cogen 160kWe lambda=1, allocation exergy	electricity, at cogen 200kWe lean burn, allocation exergy	electricity, at cogen 500kWe lean burn, allocation exergy	electricity, at cogen 1MWe lean burn, allocation exergy	electricity, at cogen 200kWe diesel SCR, allocation exergy
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	13.3	11.7	12.8	11.0	10.9	10.4	10.0	10.5
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.04	0.04	0.05	0.04	0.04	0.03	0.03	0.18
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.6E-2	2.2E-2	2.4E-2	2.0E-2	2.0E-2	1.8E-2	1.8E-2	3.3E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.0E-3	1.1E-3	1.2E-3	1.0E-3	9.4E-4	8.3E-4	7.7E-4	4.3E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.5E-3	1.4E-3	1.6E-3	1.3E-3	1.3E-3	1.2E-3	1.1E-3	3.9E-3
LCI results											
resource	Land occupation	total	m2a	7.7E-4	6.9E-4	7.6E-4	6.5E-4	6.2E-4	5.8E-4	5.5E-4	2.1E-3
air	Carbon dioxide, fossil	total	kg	6.7E-1	5.9E-1	6.5E-1	5.6E-1	5.5E-1	5.2E-1	5.1E-1	7.0E-1
air	NMVOC	total	kg	4.6E-4	4.5E-4	4.1E-4	3.5E-4	4.2E-4	4.0E-4	3.8E-4	8.2E-4
air	Nitrogen oxides	total	kg	5.3E-4	9.1E-4	4.4E-4	3.8E-4	8.5E-4	8.1E-4	7.8E-4	1.0E-3
air	Sulphur dioxide	total	kg	3.8E-4	2.8E-4	3.8E-4	3.3E-4	2.6E-4	2.4E-4	2.3E-4	1.0E-3
air	Particulates, < 2.5 um	total	kg	1.4E-5	1.3E-5	1.4E-5	1.2E-5	1.2E-5	1.1E-5	1.0E-5	5.6E-5
water	BOD	total	kg	1.0E-4	9.3E-5	9.9E-5	8.5E-5	8.2E-5	7.6E-5	7.3E-5	1.7E-3
soil	Cadmium	total	kg	1.7E-11	1.0E-11	1.1E-11	9.2E-12	8.8E-12	7.9E-12	7.4E-12	9.9E-11
Additional LCI results											
air	Methane	total	kg	3.6E-3	3.5E-3	3.2E-3	2.8E-3	3.3E-3	3.1E-3	3.0E-3	7.9E-4

Tab. 14.5 Selected LCI results and cumulative energy demands for heat at combined heat and power plants, allocation exergy.

		Name		heat, at Mini-BHKW, allocation exergy	heat, at cogen 50kWe lean burn, allocation exergy	heat, at cogen 160kWe Jakobsberg, allocation exergy	heat, at cogen 160kWe lambda=1, allocation exergy	heat, at cogen 200kWe lean burn, allocation exergy	heat, at cogen 500kWe lean burn, allocation exergy	heat, at cogen 1MWe lean burn, allocation exergy	heat, at cogen 200kWe diesel SCR, allocation exergy
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.7E-3	1.2E-3	1.3E-3	1.1E-3	1.0E-3	9.8E-4	8.9E-4	1.6E-3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.3E-4	6.6E-5	6.8E-5	5.9E-5	5.3E-5	4.8E-5	4.2E-5	2.1E-4
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	1.3E-4	8.0E-5	8.5E-5	7.3E-5	6.8E-5	6.3E-5	5.7E-5	1.9E-4
LCI results											
resource	Land occupation	total	m2a	5.1E-5	3.5E-5	3.9E-5	3.4E-5	3.2E-5	3.0E-5	2.7E-5	9.7E-5
air	Carbon dioxide, fossil	total	kg	2.7E-2	2.7E-2	3.2E-2	2.7E-2	2.6E-2	2.5E-2	2.3E-2	3.1E-2
air	NMVOC	total	kg	1.9E-5	2.1E-5	2.0E-5	1.7E-5	2.0E-5	1.9E-5	1.8E-5	3.7E-5
air	Nitrogen oxides	total	kg	2.4E-5	4.3E-5	2.2E-5	1.9E-5	4.0E-5	3.9E-5	3.6E-5	4.7E-5
air	Sulphur dioxide	total	kg	1.8E-5	1.3E-5	1.9E-5	1.6E-5	1.2E-5	1.2E-5	1.1E-5	4.5E-5
air	Particulates, < 2.5 um	total	kg	1.0E-6	6.8E-7	7.5E-7	6.5E-7	6.1E-7	5.7E-7	5.2E-7	2.6E-6
water	BOD	total	kg	8.7E-6	5.1E-6	5.4E-6	4.7E-6	4.4E-6	4.1E-6	3.7E-6	7.5E-5
soil	Cadmium	total	kg	3.3E-12	6.2E-13	6.3E-13	5.4E-13	5.1E-13	4.7E-13	4.2E-13	4.5E-12
Additional LCI results											
air	Methane	total	kg	1.4E-4	1.6E-4	1.6E-4	1.3E-4	1.5E-4	1.5E-4	1.4E-4	3.5E-5

Tab. 14.6 Selected LCI results and cumulative energy demands for electricity at combined heat and power plants, allocation energy.

		Name		electricity, at Mini-BHKW, allocation energy	electricity, at cogen 50kWe lean burn, allocation energy	electricity, at cogen 160kWe Jakobsberg, allocation energy	electricity, at cogen 160kWe lambda=1, allocation energy	electricity, at cogen 200kWe lean burn, allocation energy	electricity, at cogen 500kWe lean burn, allocation energy	electricity, at cogen 1MWe lean burn, allocation energy	electricity, at cogen 200kWe diesel SCR, allocation energy
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.1	5.5	6.1	5.3	5.4	5.6	5.5	5.9
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.11
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.1E-2	1.1E-2	1.2E-2	1.0E-2	1.0E-2	1.0E-2	9.8E-3	1.9E-2
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	4.6E-4	5.7E-4	6.0E-4	5.2E-4	4.9E-4	4.7E-4	4.4E-4	2.5E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	6.2E-4	7.0E-4	7.6E-4	6.6E-4	6.4E-4	6.3E-4	6.1E-4	2.2E-3
LCI results											
resource	Land occupation	total	m2a	3.1E-4	3.3E-4	3.8E-4	3.2E-4	3.2E-4	3.2E-4	3.1E-4	1.2E-3
air	Carbon dioxide, fossil	total	kg	2.6E-1	2.8E-1	3.1E-1	2.7E-1	2.7E-1	2.8E-1	2.8E-1	3.9E-1
air	NMVOC	total	kg	1.8E-4	2.1E-4	1.9E-4	1.7E-4	2.1E-4	2.1E-4	2.1E-4	4.7E-4
air	Nitrogen oxides	total	kg	2.1E-4	4.3E-4	2.1E-4	1.8E-4	4.2E-4	4.3E-4	4.3E-4	5.9E-4
air	Sulphur dioxide	total	kg	1.5E-4	1.3E-4	1.8E-4	1.6E-4	1.3E-4	1.3E-4	1.3E-4	5.7E-4
air	Particulates, < 2.5 um	total	kg	5.8E-6	6.2E-6	7.0E-6	6.0E-6	5.9E-6	6.0E-6	5.8E-6	3.2E-5
water	BOD	total	kg	4.1E-5	4.5E-5	4.8E-5	4.2E-5	4.2E-5	4.2E-5	4.0E-5	9.5E-4
soil	Cadmium	total	kg	8.0E-12	5.4E-12	5.6E-12	4.8E-12	4.7E-12	4.5E-12	4.3E-12	5.6E-11
Additional LCI results											
air	Methane	total	kg	1.4E-3	1.6E-3	1.5E-3	1.3E-3	1.6E-3	1.7E-3	1.6E-3	4.5E-4

Tab. 14.7 Selected LCI results and cumulative energy demands for heat at combined heat and power plants, allocation energy.

		Name		heat, at Mini-BHKW, allocation energy	heat, at cogen 50kWe lean burn, allocation energy	heat, at cogen 160kWe Jakobsberg, allocation energy	heat, at cogen 160kWe lambda=1, allocation energy	heat, at cogen 200kWe lean burn, allocation energy	heat, at cogen 500kWe lean burn, allocation energy	heat, at cogen 1MWe lean burn, allocation energy	heat, at cogen 200kWe diesel SCR, allocation energy
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.4	1.5	1.7	1.5	1.5	1.5	1.6	1.6
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.03
	cumulative energy demand	renewable energy resources, water	MJ-Eq	3.4E-3	2.9E-3	3.2E-3	2.8E-3	2.8E-3	2.8E-3	2.8E-3	5.1E-3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.9E-4	1.5E-4	1.6E-4	1.4E-4	1.3E-4	1.3E-4	1.2E-4	6.7E-4
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	2.2E-4	1.9E-4	2.1E-4	1.8E-4	1.8E-4	1.8E-4	1.7E-4	6.0E-4
LCI results											
resource	Land occupation	total	m2a	1.0E-4	9.0E-5	9.8E-5	8.6E-5	8.5E-5	8.6E-5	8.6E-5	3.2E-4
air	Carbon dioxide, fossil	total	kg	7.2E-2	7.6E-2	8.4E-2	7.3E-2	7.5E-2	7.8E-2	7.8E-2	1.1E-1
air	NMVOC	total	kg	4.9E-5	5.7E-5	5.3E-5	4.6E-5	5.7E-5	5.9E-5	5.9E-5	1.3E-4
air	Nitrogen oxides	total	kg	5.9E-5	1.2E-4	5.7E-5	5.0E-5	1.2E-4	1.2E-4	1.2E-4	1.6E-4
air	Sulphur dioxide	total	kg	4.3E-5	3.6E-5	4.9E-5	4.3E-5	3.5E-5	3.6E-5	3.6E-5	1.5E-4
air	Particulates, < 2.5 um	total	kg	1.9E-6	1.7E-6	1.9E-6	1.6E-6	1.6E-6	1.6E-6	1.6E-6	8.6E-6
water	BOD	total	kg	1.5E-5	1.3E-5	1.3E-5	1.2E-5	1.2E-5	1.2E-5	1.2E-5	2.6E-4
soil	Cadmium	total	kg	4.3E-12	1.4E-12	1.4E-12	1.3E-12	1.2E-12	1.2E-12	1.2E-12	1.5E-11
Additional LCI results											
air	Methane	total	kg	3.8E-4	4.5E-4	4.2E-4	3.7E-4	4.4E-4	4.6E-4	4.6E-4	1.2E-4

Tab. 14.8 Selected LCI results and cumulative energy demands for electricity at combined heat and power plants, allocation heat.

		Name		electricity, at Mini-BHKW, allocation heat	electricity, at cogen 50kWe lean burn, allocation heat	electricity, at cogen 160kWe Jakobsberg, allocation heat	electricity, at cogen 160kWe lambda=1, allocation heat	electricity, at cogen 200kWe lean burn, allocation heat	electricity, at cogen 500kWe lean burn, allocation heat	electricity, at cogen 1MWe lean burn, allocation heat	electricity, at cogen 200kWe diesel, allocation heat
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	cumulative energy demand	renewable energy resources, water	MJ-Eq	9.1E-4	5.9E-4	5.6E-4	4.7E-4	4.2E-4	3.2E-4	2.7E-4	4.2E-4
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.0E-4	8.1E-5	7.3E-5	6.2E-5	5.5E-5	4.1E-5	3.4E-5	5.5E-5
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	8.6E-5	6.0E-5	5.7E-5	4.8E-5	4.3E-5	3.3E-5	2.8E-5	4.3E-5
LCI results											
resource	Land occupation	total	m2a	2.4E-5	2.7E-5	2.9E-5	2.5E-5	2.2E-5	1.8E-5	1.7E-5	2.2E-5
air	Carbon dioxide, fossil	total	kg	1.2E-3	7.8E-4	7.3E-4	6.2E-4	5.5E-4	4.2E-4	3.6E-4	5.5E-4
air	NMVOC	total	kg	1.1E-6	7.2E-7	6.6E-7	5.6E-7	4.9E-7	3.7E-7	3.1E-7	5.0E-7
air	Nitrogen oxides	total	kg	3.0E-6	2.0E-6	1.9E-6	1.6E-6	1.5E-6	1.2E-6	1.0E-6	1.5E-6
air	Sulphur dioxide	total	kg	8.3E-6	4.3E-6	4.4E-6	3.7E-6	3.3E-6	2.7E-6	2.4E-6	3.3E-6
air	Particulates, < 2.5 um	total	kg	4.4E-7	3.9E-7	4.3E-7	3.7E-7	3.3E-7	2.8E-7	2.5E-7	3.3E-7
water	BOD	total	kg	4.5E-6	2.5E-6	2.5E-6	2.1E-6	1.9E-6	1.5E-6	1.3E-6	1.9E-6
soil	Cadmium	total	kg	2.2E-12	1.1E-12	9.3E-13	7.9E-13	7.0E-13	5.0E-13	4.1E-13	7.0E-13
Additional LCI results											
air	Methane	total	kg	2.3E-6	1.0E-6	9.8E-7	8.3E-7	7.4E-7	5.8E-7	5.1E-7	7.4E-7

Tab. 14.9 Selected LCI results and cumulative energy demands for heat at combined heat and power plants, allocation heat.

		Name		heat, at Mini-BHKW, allocation heat	heat, at cogen 50kWe lean burn, allocation heat	heat, at cogen 160kWe Jakobsberg, allocation heat	heat, at cogen 160kWe lambda=1, allocation heat	heat, at cogen 200kWe lean burn, allocation heat	heat, at cogen 500kWe lean burn, allocation heat	heat, at cogen 1MWe lean burn, allocation heat	heat, at cogen 200kWe diesel, allocation heat
		Location		CH	CH	CH	CH	CH	CH	CH	CH
		Unit	Unit	MJ	MJ	MJ	MJ	MJ	MJ	MJ	MJ
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	2.0	2.4	2.6	2.3	2.4	2.8	2.9	3.1
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.05
	cumulative energy demand	renewable energy resources, water	MJ-Eq	4.4E-3	4.5E-3	4.9E-3	4.3E-3	4.5E-3	4.9E-3	5.1E-3	9.7E-3
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	2.3E-4	2.3E-4	2.4E-4	2.1E-4	2.1E-4	2.2E-4	2.2E-4	1.3E-3
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	2.8E-4	2.9E-4	3.1E-4	2.8E-4	2.8E-4	3.1E-4	3.1E-4	1.1E-3
LCI results											
resource	Land occupation	total	m2a	1.3E-4	1.4E-4	1.5E-4	1.3E-4	1.4E-4	1.5E-4	1.6E-4	6.2E-4
air	Carbon dioxide, fossil	total	kg	9.9E-2	1.2E-1	1.3E-1	1.2E-1	1.2E-1	1.4E-1	1.5E-1	2.1E-1
air	NMVOC	total	kg	6.8E-5	9.0E-5	8.3E-5	7.4E-5	9.3E-5	1.1E-4	1.1E-4	2.4E-4
air	Nitrogen oxides	total	kg	8.0E-5	1.8E-4	9.0E-5	8.0E-5	1.9E-4	2.1E-4	2.2E-4	3.1E-4
air	Sulphur dioxide	total	kg	5.8E-5	5.6E-5	7.7E-5	6.8E-5	5.7E-5	6.4E-5	6.7E-5	3.0E-4
air	Particulates, < 2.5 um	total	kg	2.5E-6	2.6E-6	2.9E-6	2.5E-6	2.6E-6	2.9E-6	3.0E-6	1.6E-5
water	BOD	total	kg	1.9E-5	1.9E-5	2.0E-5	1.8E-5	1.9E-5	2.0E-5	2.1E-5	5.0E-4
soil	Cadmium	total	kg	4.9E-12	2.1E-12	2.1E-12	1.9E-12	1.9E-12	2.1E-12	2.1E-12	2.9E-11
Additional LCI results											
air	Methane	total	kg	5.3E-4	7.0E-4	6.5E-4	5.8E-4	7.3E-4	8.2E-4	8.6E-4	2.3E-4

14.3.2 Analysis

The cumulative carbon dioxide emissions per kWh electricity at the natural gas combined heat and power plants range between about 510 g/kWh_e (1 MW_e lean burn motor) and about 670 g/kWh_e ("Mini-BHKW") for allocation exergy (Fig. 14.3). They tend to decrease within the natural gas group with increasing capacity. The reason for the tendency is mainly the higher electric efficiency of larger plants. To a minor extent the decreasing material requirements per kWh for increasing capacity of the same technology play a role. The diesel CHP has the highest cumulative CO_2 emissions per kWh electricity (about 700 g/kWh_e) because of the high emission factor of diesel (or oil) related to the energy content of the fuel and because of the relatively high contribution from the rest of the chain. The corresponding cumulative CO_2 emissions per MJ (per kWh, resp.) heat for exergy allocation of natural gas CHP plants available at the market are between about 23 g/MJ_{th}, i.e. about 83 g/kWh_{th} (1 MW_e lean burn motor) and about 27 g/MJ_{th}, i.e. about 100 g/kWh_{th} (50-160 kW_e CHP und "Mini-BHKW"). The value for the diesel CHP is about 31 g/MJ_{th}, i.e. about 112 g/kWh_{th}. In all cases, the total CO_2 emissions are dominated by emissions during the operation of the plant. CO_2 emissions from the rest of the chain play a secondary but still significant role (for the relative proportion, see chapter on the natural gas systems). The cumulative energy demand (CED) of the natural gas CHP shows a tendency similar to the CO_2 emissions because it includes mainly the energy content of the natural gas burned in the plant.

The cumulative NO_x emissions per kWh electricity or heat differ mainly because of different technologies (Fig. 14.4). In a CHP with lambda1 motor, the direct NO_x emissions from the plant are reduced by a three-way catalyst. For the modelled lambda1 CHP, the contributions of the indirect NO_x emissions from the rest of the chain are higher than the direct NO_x emissions from power plant operation. Nevertheless, the cumulative NO_x emissions of the lambda1 CHP remain still lower than the cumulative NO_x emissions of the lean burn CHP without catalysts or the cumulative NO_x emissions of the diesel CHP. Within the group of natural gas lean burn motors, the exergy-allocated NO_x emissions per kWh electricity tend to decrease with increasing capacity, similarly to the CO_2 emissions.

14.4 Conclusions

Different capacity classes and different technologies of combined cycle power plants have been considered. The natural gas combined heat and power plants have lower cumulative carbon dioxide emissions and NO_x emissions than the modelled diesel plant. Natural gas combined heat and power plants with three-way catalysts have the lowest cumulative nitrogen oxide emissions, although the technology with catalyst increases slightly the nitrogen oxide emissions from the rest of the chain. The results per kWh electricity or per MJ heat depend significantly on the allocation method.

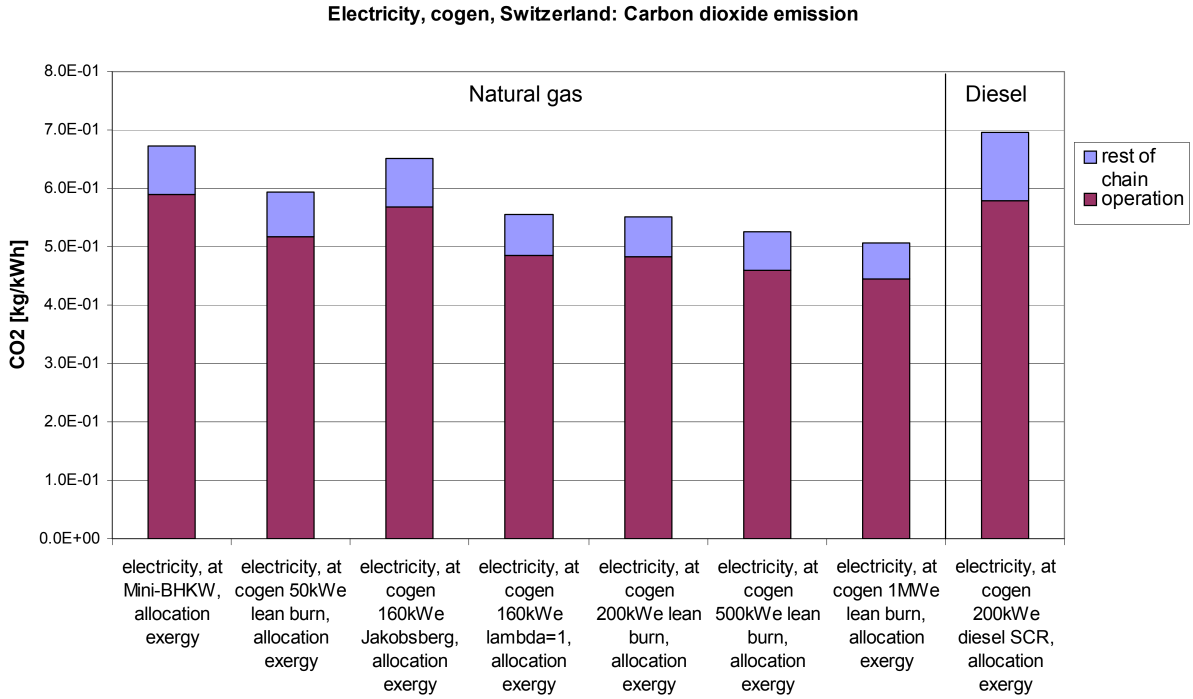

Fig. 14.3 Cumulative CO_2 emissions per kWh electricity at combined heat and power plants, allocation exergy.

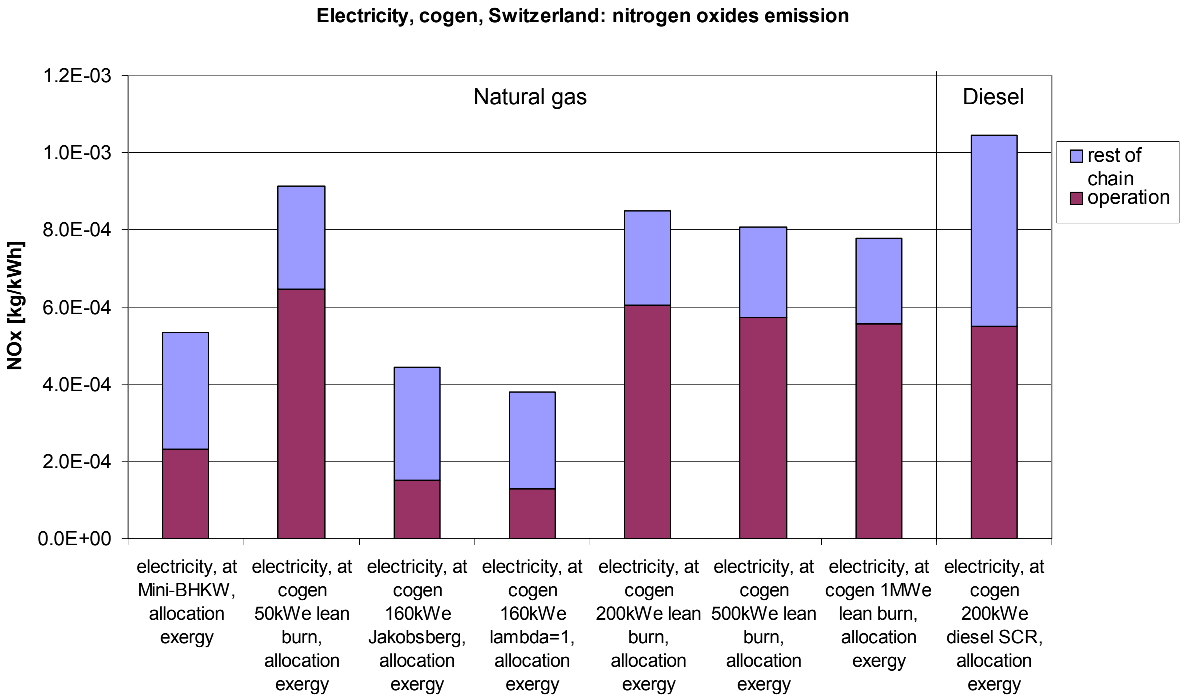

Fig. 14.4 Cumulative NO_x emissions per kWh electricity at combined heat and power plants, allocation exergy.

14.5 References

ASUE 2001	ASUE (2001) BHKW-Kenndaten 2001. Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V., Kaiserslautern, Germany.
Bauer 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.). Final report ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Berdowski et al. 2002	Berdowski J., Visschedijk A., Creemers E. and Pulles T. (2002) CEPMEIP Emission factors for particulate matter. TNO, Apeldoorn, The Netherlands, retrieved from: http://spiritas.host.sk/tno/cepmeip/downloads.php.
BUWAL 2001a	BUWAL (2001a) Arbeitsblatt Emissionsfaktoren Feuerungen. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.
BUWAL 2001b	BUWAL (2001b) Massnahmen zur Reduktion der PM10-Emissionen. Um-welt-Materialien Nr. 136, Luft. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.
CEIDARS 2001	CEIDARS (2001) Speciation Profiles and Size Fractions. California emission inventory and reporting system (CEIDARS), US, retrieved from: http://www.arb.ca.gov/emisinv/speciate/speciate.htm.
Ecopower 2001	Ecopower (2001) Installationsvorschriften Mini-BHKW Erdgas/Propangas. Version 22D. Oktober 2001. Ecopower, Oerlingen, Switzerland, retrieved from: www.ecopower.ch.
Ecopower 2002	Ecopower (2002) Technische Daten zum ecopower Mini-BHKW Erdgas / Propangas netzparallel. Ecopower, Oerlingen, Switzerland.
Eicher & Rigassi 2002	Eicher H. and Rigassi R. (2002) Technologiemonitoring im Bau- und Energiebereich, Vortrag 13.9.2002. Eicher+Pauli AG, Basel, retrieved from: www.eicher-pauli.ch.
Eicher+Pauli 2002	Eicher+Pauli (2002) Mitteilung der Firma Eicher+Pauli AG (Herr Zwei-acker). Eicher+Pauli AG, Basel.
EUROMOT 2002	EUROMOT (2002) Stationary Engines Emissions Abatement With a view to the Austrian Standard. The European Association of Internal Combustion En-gine Manufacturers, Frankfurt, Germany.
ExternE 1999	ExternE (1999) Externalities of fuel cycles. ExternE - Externalities of energy. Volume 7: Methodology 1998 update. EUR 19083. European Commission, DG XII, Science, Research and Development, Brussels.
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.). Final report ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.
Gantner et al. 1999	Gantner U., Jakob M. and Hirschberg S. (1999) Methoden und Analysen - Grundlagen sowie ökologische und ökonomische Vergleiche von zukünftigen Energieversorgungsvarianten der Schweiz; Schlussentwurf, Arbeitsmaterial. Paul Scherrer Institut, Villigen, Switzerland.
Heck 2004	Heck T. (2004) 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. Do-nes R.).

Final report ecoinvent 2000 No. 6, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.ch.

Hupperich & Schiffgens 1994	Hupperich P. and Schiffgens H.-J. (1994) Verbrennungsmotor - Blockheizkraftwerke; Programmgruppe Technologiefolgenforschung; IKARUS Instrumente für Klimags-Reduktionsstrategien, Teilprojekt 8 "Querschnittstechniken". Forschungszentrum Jülich GmbH, Jülich, Germany.
IIASA 2002	IIASA (2002) RAINS PM Web. International Institute for Applied Systems Analysis (IIASA), retrieved from: http://www.iiasa.ac.at/~rains/cgi-bin/rains_pm.pl.
IWK 2002	IWK (2002) Datenblatt Blockheizkraftwerke. Firma IWK Integrierte Wärme und Kraft AG, Winterthur, Switzerland.
Jenbacher 2002	Jenbacher (2002) Technische Daten BHKW. Jenbacher AG, Jenbach, Austria.
Kühnis & Eicher 1993	Kühnis F. and Eicher H. P. (1993) Emissions-Minimierung bei Gasmotoren, NEFF Projekt Nr. 458 Schlussbericht. 193213. Eicher + Pauli AG, ENET, Basel.
Lorenz 2002	Lorenz K. (2002) Swissmotor-BHKW. In: Tagungsband zur Tagung "Entwicklungstendenzen der Wärmekraftkopplung: Brennstoffzellen und Blockheizkraftwerke", Zürich-Oerlikon, 13.Nov. 2002. Schweizerischer Fachver-band für Wärmekraftkopplung, Zürich.
MENAG 2002	MENAG (2002) Produktdokumentation der MENAG Group, Version 10/2002. DIMAG Energy, MENAG ENERGIE GmbH, Niederdorf, Schweiz.
MENAG Service 2002	MENAG Service (2002) Betriebsunterlagen der Firma MENAG Service AG/DIMAG. MENAG Service AG/DIMAG, Niederdorf, Switzerland.
Schmieder 2002	Schmieder E. (2002) Mikro-WKK-Anlagen mit Stirlingmotoren: Stand der Technik, Vorteile. In: Tagungsband zur Tagung "Entwicklungstendenzen der Wärmekraftkopplung: Brennstoffzellen und Blockheizkraftwerke", Zürich-Oerlikon, 13.Nov. 2002. Schweizerischer Fachverband für Wärmekraftkopplung, Zürich.
Ulli 2002	Ulli A. (2002) Praxiserfahrung mit Wassereinspritzung für Diesel-BHKW. In: Tagungsband zur Tagung "Entwicklungstendenzen der Wärmekraftkopplung: Brennstoffzellen und Blockheizkraftwerke", Zürich-Oerlikon, 13.Nov. 2002. Schweizerischer Fachverband für Wärmekraftkopplung, Zürich.
Viessmann 2002	Viessmann (2002) Vitobloc Blockheizkraftwerke Datenblatt. Viessmann Werke GmbH & Co, Allendorf, Germany, retrieved from: www.viessmann.de.
WKK-Fachverband 2001	WKK-Fachverband (2001) Wärme-Kraft-Kopplung Vol. 3. WKK-Fachverband, Liestal.
WKK-Fachverband 2002	WKK-Fachverband (2002) Webseite des WKK-Fachverbandes, Technik. WKK-Fachverband, Zürich, retrieved from: http://www.waermekraftkopplung.ch/technik/.

15 Electricity mix and electricity network

Authors: Rolf Frischknecht and Mireille Faist Emmenegger, ESU-services

15.1 Introduction

This chapter describes the models applied for the calculation of average electricity production and supply mixes (at the busbar of power stations) in the UCTE, CENTREL and NORDEL countries as well as Great Britain and Ireland. The models for the two companies European aluminium industry and the Swiss Federal Railways (SBB) are also presented. These models represent the share of the different production technologies (e.g. oil, natural gas, hydropower, wind power, nuclear etc.) in one country (production mix), as well as the mix of technologies, including all imports, corresponding to the electricity dispatched at the grid (supply mix of one country).

The system model "Electricity network" describes the distribution of electricity divided in the high, medium and low voltage networks. It includes the infrastructure of the distribution (e.g. copper of transmission lines) and its land use as well as losses in the networks, SF_6 emissions of switching stations and heavy metal leaching from wooden masts.

15.2 System description

15.2.1 Electricity mix

Electricity production is modelled individually for each technology and described in the preceding chapters of this report. Country mixes are established with the average production of the year 2000. The following energy sources are taken into account: hard coal, lignite, fuel oil, natural gas, industry gas, hydropower (from run-of-river, storage, and pumped storage power plants), nuclear power (boiling water and pressurised water reactors), wind power, photovoltaic, biomass, biogas (both addressed with wood co-generation) and other production technologies. The latter category comprises waste incineration plants which produce electricity. According to the ecoinvent methodology, electricity is considered as a by-product and all environmental impacts are allocated to the waste rather than to the electricity.

The ecoinvent Data v.1.1 considers the electricity mix of the following organizations and countries: UCTE, with Austria, Belgium, Germany, Spain, France, Greece, Slovenia, Croatia, Bosnia Herzegovina, Republic Yugoslavia (Serbia und Montenegro), Macedonia, Luxemburg, the Netherlands, Portugal and Switzerland; CENTREL, with Czech Republic, Hungary, Poland and Slovakia; NORDEL, with Denmark, Finland, Norway, and Sweden (Island as fifth NORDEL-country is not considered here); United Kingdom and Ireland. In 2001, the CENTREL countries became official full members of the UCTE network. However, in ecoinvent Data v1.1 the official legal state of UCTE in the year 2000 is represented.

The main data sources used to describe the mixes are national statistics and communications, and statistics of international organisations (such as CENTREL 2001; EURELECTRIC 2001; IEA 2001; IEA/OECD 2002; NORDEL 2001; UCTE 2001).

15.2.2 Production mix

The production mix model considers domestic production only. It includes the production of all power plants situated within the political borders of a country. No attention is paid to contracts and property rights, i.e., electricity trade with foreign countries is not considered. The shares of the different technologies for the production mix of the studied countries are shown in Tab. 15.1 and Tab. 15.2.

15.2.3 Supply mix

The supply mix model is an approximation of the actual electricity mix provided to customers at the grid and exported to third countries. All imports are attributed to the domestic production of a country. Ideally, the imports are represented by the supply mix of technologies of the exporting countries. These assumptions are probably the best approximation taking into account the fact that production and sale of electricity take place independently from each other. However, to avoid artificial feedback loops in the modelling, imported electricity is approximated with the production mixes of the exporting countries. Electricity imports and exports are calculated with the physical electricity flows except for electricity trade with Switzerland, as for the other countries no data on the traded flows are available. The shares of the different domestic production technologies and the imports for the supply mixes of the studied countries are shown in Tab. 15.1 and Tab. 15.2.

Tab. 15.1 Production and supply mixes of the UCTE countries: shares of domestic technologies and imports in year 2000

		Domestic production technologies						Imports	Total
		fossil	nuclear	hydro	pumped storage	new renewable	waste		
Austria	production	20.2		77.1	2.6	0.1			100.0
	supply	14.8		56.6	1.9	0.1		26.6	100.0
Belgium	production	38.8	57.6	0.6	1.6	0.3	1.1		100.0
	supply	33.8	50.2	0.5	1.4	0.3	1.0	12.8	100.0
Bosnia Herzegovina	production	51.5		48.5					100.0
	supply	46.7		44.0				9.3	100.0
Croatia	production	41.2		55.1	3.6				100.0
	supply	23.8		31.8	2.1			42.3	100.0
France	production	9.0	76.6	12.8	0.9	0.4	0.4		100.0
	supply	8.9	75.9	12.7	0.9	0.4	0.4	0.9	100.0
Germany	production	62.2	30.4	4.3	0.5	2.0	0.5		100.0
	supply	56.8	27.7	3.9	0.5	1.8	0.5	8.7	100.0
Greece	production	90.7		7.3	0.8	0.9	0.3		100.0
	supply	87.7		7.0	0.8	0.9	0.3	3.3	100.0
Luxemburg	production	18.7		10.4	64.1	2.7	4.2		100.0
	supply	2.8		1.6	9.7	0.4	0.6	84.8	100.0
Macedonia	production	83.5		16.5					100.0
	supply	78.4		15.5				6.1	100.0
the Netherlands	production	89.5	4.4	0.2		2.0	3.9		100.0
	supply	70.2	3.5	0.1		1.6	3.1	21.6	100.0
Portugal	production	67.9		27.1	0.9	2.9	1.2		100.0
	supply	61.1		24.4	0.8	2.6	1.0	10.0	100.0
Serbia and Montenegro	production	65.1		33.4	1.5				100.0
	supply	60.5		31.1	1.4			7.1	100.0
Slovenia	production	34.5	35.6	29.5		0.2	0.3		100.0
	supply	23.9	24.7	20.5		0.1	0.2	30.6	100.0
Switzerland	production	1.6	37.5	56.9	1.3	0.0	2.6		100.0
	supply	1.0	23.4	35.6	0.8	0.0	1.6	37.5	100.0

Tab. 15.2 Production and supply mixes of the CENTREL and NORDEL countries as well as United Kingdom and Ireland: shares of domestic technologies and imports in year 2000

		Domestic production technologies						Imports	Total
		fossil	nuclear	hydro	pumped storage	new renewable	waste		
Czech Republic	production	77.1	18.6	2.5	0.8	0.7	0.3		100.0
	supply	68.4	16.5	2.3	0.7	0.6	0.2	11.3	100.0
Hungary	production	59.0	40.2	0.5		0.0	0.3		100.0
	supply	45.7	31.1	0.4		0.0	0.2	22.6	100.0
Poland	production	96.6		1.5	1.5	0.2	0.2		100.0
	supply	94.4		1.5	1.4	0.2	0.2	2.3	100.0
Slovakia	production	29.6	53.5	16.1	0.9				100.0
	supply	24.2	43.8	13.2	0.7			18.0	100.0
Denmark	production	82.7		0.1		14.0	3.2		100.0
	supply	66.3		0.1		11.3	2.6	19.8	100.0
Finland	production	32.8	32.1	21.5		13.6			100.0
	supply	27.5	27.0	18.0		11.5		16.1	100.0
Norway	production	0.2		99.1	0.4	0.2	0.1		100.0
	supply	0.2		98.0	0.4	0.2	0.1	1.0	100.0
Sweden	production	3.6	38.6	54.9		2.8	0.2		100.0
	supply	3.2	34.2	48.6		2.5	0.2	11.4	100.0
United Kingdom	production	74.8	21.7	1.4	0.7	1.4			100.0
	supply	71.9	20.9	1.3	0.7	1.4		3.8	100.0
Ireland	production	93.4		3.7	1.3	1.5			100.0
	supply	93.4		3.7	1.3	1.5			100.0

Specific company mixes for companies with own electricity generation systems can be built using the data sets for the different electricity producing technologies. However, network losses and emissions must be taken additionally into account. Two company models (European aluminium industry and the Swiss Federal Railways, SBB) have been considered (EAA 2000, and personal communication of SBB). The share of the different technologies is summarized in Tab. 15.3.

Tab. 15.3: Fuel share of the supply mixes of the European aluminium industry and the Swiss Federal Railways

	Swiss Federal Railways (SBB)	European aluminium industry
Fossil	-	32.8%
Hydro	90.7%	52.6%
Nuclear	6.8%	14.6%
Import	2.5%	-

15.2.4 Infrastructure of the electricity network

The infrastructure includes: the material requirements for lines, cables, pylons, transformers, buildings, and switching stations; land use; transport of materials; and, disposal of concrete, wood and other materials. Heavy metal emissions in soil from coating of wooden masts through leaching is also comprised in the infrastructure data sets. The inventories consider separately the infrastructure for the high and medium voltage transmission networks, the low voltage distribution network, and an average

European long distance transmission network. The data sets (except for the long distance network) are based on the inventory of the Swiss network. They are also used as an estimate for the networks of all European countries modelled in ecoinvent Data v1.1.

The infrastructure lifetime is evaluated to be 30-40 years. The Swiss network comprised 230'190 km cables and 109'990 km overhead electric lines in 1988. In 2000 the total electricity supply in Switzerland was 56.3 TWh. Copper requirements are estimated to be 0.5 to 1.5 t/km conductor[20]. There are about 2.7 millions pylons in the network, about 90% of them are wooden masts. These are attributed to 80% to the low voltage network, the rest to the medium voltage network. The total stock of SF_6 used in power switching stations is 240 t; 90 % of this figure is attributed to the high voltage network, the rest to the medium voltage network along with the attribution of transformers and switching stations to the high voltage and medium voltage, respectively.

15.2.5 Distribution of electricity

Electricity mixes are established at the busbar of power plants. Electricity supply, however, occurs at different voltage levels. Therefore three voltage levels (high, medium and low voltage) are distinguished. Transmission losses as well as infrastructure and SF_6 emissions are considered in the data sets "electricity, high/medium/low voltage, at grid" (country). The country specific SF_6 losses and leak figures are shown in Tab. 15.4.

Electricity losses on the different voltage levels are calculated on the basis of the total network losses of the year 2000 and on a fixed share of the losses among the voltage levels (7 % of the total losses occur on high voltage, 13 % on medium voltage, and 80 % on low voltage level). This partitioning is based on investigations made in the nineties in Switzerland (Frischknecht et al. 1994). For most countries, country-specific total network losses are applied. However, the shares of losses in the three voltage levels are calculated on the basis of the Swiss data, except for Finland which has a very different structure of electricity supply and use.

There are only very few specific data on the SF_6 emission rates (in % per year of stock of SF_6) in the different countries. The emission rate of Germany is used for the remaining UCTE and CENTREL countries, the emission rate of Denmark for NORDEL countries, and the emission rate of United Kingdom for Ireland. Country-specific information showed that the total stock of SF_6 per kWh electricity is similar for all data sets and represents the figure for Switzerland. Leakages of SF_6 are estimated to be 1 % per year of the stock in Switzerland, Austria and the NORDEL countries. In Germany, the yearly leakages are 2.1 %, in France about 0.9 %. N_2O emissions of the electricity high voltage transmission due to corona effect are 5 kg/GWh electricity and the ozone emissions 4.5 kg/GWh. No country specific data are available.

[20] Three to four conductors form one cable.

Tab. 15.4: Network losses of European countries, total and calculated losses for the three voltage levels and yearly SF_6 leakages in percent of total SF_6 stock

		Total	High voltage	Medium voltage	Low voltage	SF_6-emissions
		%	%	%	%	%/a
Belgium	BE	4.6	0.31	0.63	6.1	2.1
Germany	DE	4.9	0.33	0.68	6.6	2.1
Spain	ES	10.0	0.64	1.33	13.4	2.1
France	FR	7.2	0.47	0.97	9.6	0.86
Greece	GR	9.4	0.60	1.25	12.5	2.1
Italy	IT	6.9	0.45	0.94	9.2	2.1
Slovenia	SI	15.2	0.93	1.94	20.3	2.1
Croatia	HR	18.2	1.09	2.26	24.2	2.1
Macedonia	MK	15.2	0.93	1.94	20.3	2.1
Bosnia Herzegovina	BA	15.2	0.93	1.94	20.3	2.1
Serbia und Montenegro	CS	16.3	0.99	2.06	21.7	2.1
Luxemburg	LU	7.5	0.49	1.02	10.0	2.1
the Netherlands	NL	7.5	0.49	1.02	10.0	2.1
Austria	AT	5.3	0.35	0.73	7.0	1.0
Portugal	PT	8.5	0.55	1.14	11.3	2.1
Switzerland	CH	7.5	0.49	1.02	10.0	1.0
Czech Republic	CZ	9.0	0.58	1.20	12.0	2.1
Hungary	HU	15.1	0.93	1.92	20.2	2.1
Poland	PL	7.9	0.51	1.06	10.5	2.1
Slovakia	SK	7.6	0.49	1.02	10.1	2.1
Denmark	DK	6.6	0.43	0.90	8.7	1.0
Finland	FI	3.8	0.18	0.60	10.8	1.0
Norway	NO	8.2	0.53	1.10	10.9	1.0
Sweden	SE	8.8	0.57	1.18	11.7	1.0
United Kingdom	GB	7.5	0.49	1.02	10.0	4.3
Ireland	IE	9.7	0.62	1.29	13.0	4.3
UCTE network		7.1	0.47	0.97	9.5	1.7
CENTREL network		9.0	0.58	1.21	12.0	2.1
NORDEL network		7.5	0.48	1.02	11.0	1.0
Swiss Federal Railways (SBB)	CH	7.5	0.49	1.02	10.0	1.0
European Aluminium Industry	GLO	7.1	0.5	1.0	9.5	1.7

15.3 Cumulative results and interpretation

Selected LCI results and values for the cumulative energy demand are presented and discussed in this Section. For use and limitations of the results presented in the following tables, please refer to Chapter 3.2. The results presented here cover the supply mixes of all countries modelled within ecoinvent Data v1.1.

15.3.1 UCTE countries

The technology shares of the fossil, nuclear, and hydro power plants as well as power plants with other technologies are very well reflected by the indicators for the cumulative energy demand (see Tab. 15.5 and Tab. 15.6). Greece has with 15.9 MJ_{eq}/kWh for the CED fossil the highest fossil energy demand of the UCTE countries, France with 10.4 MJ_{eq}/kWh for CED nuclear the highest nuclear energy demand.

Hydropower is an important part of the production mix in Switzerland, Austria, and countries of the former Yugoslavia. Nuclear energy is (besides France) important in Belgium, Switzerland, Luxemburg, Spain and Germany. High land use figures are due to coal and biomass electricity production. CO_2 emissions are high for countries with a high fossil share. BOD emissions are in proportion to the share of electricity produced by oil power plants.

Tab. 15.5 Selected LCI results and cumulative energy demand for supply mixes of UCTE countries, part 1

		Name		electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix
		Location		BE	DE	ES	FR	GR	IT	BA	HR
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	4.04	7.38	5.64	1.03	15.93	7.98	6.49	6.31
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	7.51	3.72	4.20	10.35	0.20	1.10	0.07	2.16
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.09	0.30	0.70	0.60	0.37	1.03	2.13	1.75
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.01	0.25	0.32	0.00	0.13	0.03	0.00	0.00
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.08	0.08	0.07	0.06	0.01	0.01	0.00	0.02
LCI results											
resource	Land occupation	total	m2a	9.1E-3	1.3E-2	1.4E-2	7.3E-3	5.9E-3	4.3E-3	8.6E-3	1.8E-2
air	Carbon dioxide, fossil	total	kg	3.3E-1	6.2E-1	4.8E-1	9.1E-2	1.0E+0	5.7E-1	6.8E-1	4.7E-1
air	NMVOC	total	kg	1.0E-4	1.0E-4	8.7E-5	2.9E-5	1.2E-4	2.5E-4	2.4E-5	1.3E-4
air	Nitrogen oxides	total	kg	6.2E-4	6.0E-4	1.7E-3	2.7E-4	1.3E-3	1.3E-3	1.6E-3	1.1E-3
air	Sulphur dioxide	total	kg	7.4E-4	5.2E-4	5.2E-3	3.7E-4	5.2E-3	2.4E-3	1.2E-2	4.6E-3
air	Particulates, < 2.5 um	total	kg	6.1E-5	6.2E-5	2.0E-4	3.0E-5	6.2E-4	7.6E-5	8.1E-4	1.3E-4
water	BOD	total	kg	1.0E-4	9.9E-5	2.7E-4	7.5E-5	6.0E-4	9.8E-4	3.1E-5	6.1E-4
soil	Cadmium	total	kg	1.4E-10	1.2E-10	1.0E-10	1.0E-10	1.4E-11	1.9E-11	4.5E-12	2.5E-11
Further LCI results											
air	Sulfur hexafluoride	total	kg	8.1E-10	6.8E-10	9.4E-10	4.3E-10	7.3E-10	1.4E-9	1.5E-10	9.3E-10
air	Radon-222	total	kBq	4.4E+2	2.2E+2	2.4E+2	6.0E+2	1.2E+1	6.4E+1	4.1E+0	1.3E+2

Tab. 15.6 Selected LCI results and cumulative energy demand for supply mixes of UCTE countries, part 2

		Name		electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix	electricity mix
		Location		MK	SI	CS	LU	NL	AT	PT	CH
		Unit	Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	12.63	3.98	10.24	7.06	9.53	3.50	7.88	1.42
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.13	3.17	0.31	4.73	1.46	1.05	0.50	5.88
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.75	1.87	1.43	0.23	0.05	2.84	1.31	1.92
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.01	0.00	0.00	0.23	0.16	0.04	0.09	0.03
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.00	0.04	0.01	0.09	0.19	0.03	0.45	0.03
LCI results											
resource	Land occupation	total	m2a	7.1E-3	8.1E-3	6.4E-3	1.5E-2	1.0E-2	7.6E-3	1.7E-2	6.4E-3
air	Carbon dioxide, fossil	total	kg	1.0E+0	3.6E-1	8.8E-1	5.7E-1	6.6E-1	2.7E-1	5.8E-1	1.1E-1
air	NMVOC	total	kg	3.9E-5	4.8E-5	3.9E-5	1.2E-4	1.1E-4	8.3E-5	1.8E-4	3.2E-5
air	Nitrogen oxides	total	kg	2.7E-3	8.6E-4	1.6E-3	6.4E-4	8.9E-4	3.8E-4	2.0E-3	1.8E-4
air	Sulphur dioxide	total	kg	2.2E-2	5.1E-3	1.0E-2	5.9E-4	4.5E-4	3.8E-4	4.8E-3	1.9E-4
air	Particulates, < 2.5 um	total	kg	7.0E-4	1.4E-4	1.4E-3	6.6E-5	5.3E-5	3.9E-5	1.6E-4	2.4E-5
water	BOD	total	kg	6.4E-5	1.4E-4	6.6E-5	1.0E-4	1.8E-4	7.8E-5	7.6E-4	5.1E-5
soil	Cadmium	total	kg	6.9E-12	6.2E-11	1.2E-11	1.4E-10	3.2E-10	3.8E-11	7.9E-10	4.8E-11
Further LCI results											
air	Sulfur hexafluoride	total	kg	1.9E-10	3.8E-10	2.1E-10	7.8E-10	1.1E-9	4.1E-10	1.6E-9	3.1E-10
air	Radon-222	total	kg	7.4E+0	1.8E+2	1.8E+1	2.7E+2	8.5E+1	6.1E+1	2.9E+1	3.4E+2

15.3.2 CENTREL countries

Poland has a high share of fossil energy (12.2 MJ_{eq}/kWh) and therefore high CO_2 emissions (1.1 kg/kWh), as shown in Tab. 15.7. Czech Republic, Hungary and Slovakia follow in descending order. Renewable electric energy production has only a very small share in the CENTREL countries.

Tab. 15.7 Selected LCI results and cumulative energy demand for supply mixes of CENTREL countries

		Name		electricity mix	electricity mix	electricity mix	electricity mix
		Location		CZ	HU	PL	SK
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	8.64	7.76	12.71	5.21
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.32	5.36	0.27	5.96
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.14	0.23	0.11	0.63
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.00	0.01	0.01	0.00
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.15	0.01	0.08	0.04
LCI results							
resource	Land occupation	total	m2a	1.1E-2	5.0E-3	2.8E-2	1.1E-2
air	Carbon dioxide, fossil	total	kg	9.1E-1	5.7E-1	1.1E+0	4.3E-1
air	NMVOC	total	kg	7.7E-5	1.7E-4	8.0E-5	8.8E-5
air	Nitrogen oxides	total	kg	1.8E-3	1.3E-3	1.9E-3	1.0E-3
air	Sulphur dioxide	total	kg	2.3E-3	5.9E-3	7.4E-3	2.1E-3
air	Particulates, < 2.5 um	total	kg	1.5E-4	1.5E-4	4.1E-4	1.6E-4
water	BOD	total	kg	6.3E-5	3.9E-4	1.2E-4	6.2E-5
soil	Cadmium	total	kg	2.4E-10	2.2E-11	7.4E-11	5.0E-11
Further LCI results							
air	Sulfur hexafluoride	total	kg	4.7E-10	7.2E-10	1.0E-9	5.6E-10
air	Radon-222	total	kg	1.3E+2	3.1E+2	1.6E+1	3.5E+2

15.3.3 NORDEL countries

Norway supply mix is almost entirely based on domestic hydropower (4.5 MJ_{eq}/kWh) and therefore has very low CO_2 emissions (8.7 g/kWh, see Tab. 15.8). Finland has a high share of domestic biomass based electricity production (paper industry), approximated with wood co-generation. Land use is accordingly high (470 cm^2a/kWh). Sweden has like Switzerland a production mix based mostly on hydropower and nuclear. Sweden has less fossil based imports than Switzerland and therefore has lower CO_2 emissions.

Tab. 15.8 Selected LCI results and cumulative energy demand for supply mixes of NORDEL countries

		Name		electricity mix	electricity mix	electricity mix	electricity mix
		Location		DK	FI	NO	SE
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	7.39	3.61	0.09	0.47
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	0.51	4.06	0.05	4.33
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.72	1.10	4.58	2.62
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	1.44	0.02	0.01	0.06
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.33	2.41	0.04	0.48
LCI results							
resource	Land occupation	total	m2a	1.8E-2	4.7E-2	4.5E-3	1.5E-2
air	Carbon dioxide, fossil	total	kg	5.1E-1	2.7E-1	8.7E-3	4.1E-2
air	NMVOC	total	kg	1.1E-4	8.3E-5	6.0E-6	2.3E-5
air	Nitrogen oxides	total	kg	7.5E-4	6.5E-4	3.8E-5	1.3E-4
air	Sulphur dioxide	total	kg	1.4E-3	6.5E-4	1.9E-5	8.2E-5
air	Particulates, < 2.5 um	total	kg	6.7E-5	2.9E-4	1.7E-5	6.4E-5
water	BOD	total	kg	3.5E-4	1.1E-4	9.0E-6	5.2E-5
soil	Cadmium	total	kg	5.6E-10	4.2E-9	6.9E-11	8.5E-10
Further LCI results							
air	Sulfur hexafluoride	total	kg	9.8E-10	7.3E-10	1.5E-10	3.0E-10
air	Radon-222	total	kg	2.9E+1	2.4E+2	2.9E+0	2.5E+2

15.3.4 United Kingdom, Ireland, European Aluminium Industry and SBB supply mixes.

CO_2 emissions in United Kingdom and Ireland are high (530 g/kWh and 770 g/kWh, respectively) due to the high fossil based electricity production (see Tab. 15.9). SBB mix is mostly based on hydropower and has very low CO_2 emissions (15 g/kWh). CO_2 emissions (320 g/kWh) of the European Aluminium industry mix are in the middle range.

Tab. 15.9 Selected LCI results and cumulative energy demand for supply mixes of United Kingdom, Ireland, European Aluminium Industry and SBB

		Name		electricity mix	electricity mix	electricity mix, SBB	electricity mix, aluminium industry
		Location		GB	IE	CH	GLO
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	7.54	11.48	0.19	4.08
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	3.13	0.12	1.05	1.89
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.10	0.19	4.11	2.34
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.04	0.16	0.00	0.00
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.25	0.10	0.00	0.01
LCI results							
resource	Land occupation	total	m2a	1.5E-2	1.1E-2	4.4E-3	9.5E-3
air	Carbon dioxide, fossil	total	kg	5.3E-1	7.7E-1	1.5E-2	3.2E-1
air	NMVOC	total	kg	9.1E-5	2.2E-4	7.3E-6	5.2E-5
air	Nitrogen oxides	total	kg	1.0E-3	1.5E-3	5.0E-5	6.7E-4
air	Sulphur dioxide	total	kg	1.2E-3	3.8E-3	5.2E-5	1.2E-3
air	Particulates, < 2.5 um	total	kg	9.9E-5	1.1E-4	1.7E-5	8.2E-5
water	BOD	total	kg	2.9E-4	7.9E-4	1.5E-5	1.5E-4
soil	Cadmium	total	kg	4.2E-10	1.6E-10	6.6E-12	9.3E-12
Further LCI results							
air	Sulfur hexafluoride	total	kg	9.3E-10	1.5E-9	1.2E-10	6.6E-10
air	Radon-222	total	kg	1.8E+2	6.8E+0	6.1E+1	1.1E+2

15.3.5 Low, medium and high voltage supply mixes in year 2000

The following selected LCI results and cumulative energy demand for the Swiss, UCTE, CENTREL and NORDEL electricity mixes take into account the grid losses as well as the material and energy requirements for the infrastructure of the network. This is necessary to assess the electricity at consumer level. Infrastructure requirements have in general only little influence on the overall results shown here. The network losses double from high voltage to medium voltage and are ten times higher in the low voltage than in the medium voltage level. These increasing losses with descending voltage level can well be recognized in the results (see Tab. 15.10 to Tab. 15.12). Exceptions are the SF_6 emissions, which increase over proportional from the high to medium voltage, and BOD emissions, which double from medium to low voltage.

Tab. 15.10 Selected LCI results and cumulative energy demand for the Swiss supply mix at low, medium and high voltage and at busbar

		Name		electricity mix	electricity, high voltage, at grid	electricity, medium voltage, at grid	electricity, low voltage, at grid
		Location		CH	CH	CH	CH
		Unit	Unit	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.42	1.43	1.45	1.64
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	5.88	5.94	6.00	6.61
	cumulative energy demand	renewable energy resources, water	MJ-Eq	1.92	1.94	1.96	2.16
	cumulative energy demand	renewable energy resources, wind, solar,	MJ-Eq	0.03	0.03	0.03	0.04
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.03	0.03	0.03	0.04
LCI results							
resource	Land occupation	total	m2a	6.4E-3	6.5E-3	6.8E-3	8.8E-3
air	Carbon dioxide, fossil	total	kg	1.1E-1	1.2E-1	1.2E-1	1.3E-1
air	NMVOC	total	kg	3.2E-5	3.3E-5	3.4E-5	4.1E-5
air	Nitrogen oxides	total	kg	1.8E-4	1.8E-4	1.9E-4	2.3E-4
air	Sulphur dioxide	total	kg	1.9E-4	2.0E-4	2.1E-4	2.9E-4
air	Particulates, < 2.5 um	total	kg	2.4E-5	2.4E-5	2.5E-5	3.6E-5
water	BOD	total	kg	5.1E-5	5.4E-5	6.0E-5	1.1E-4
soil	Cadmium	total	kg	4.8E-11	4.9E-11	5.0E-11	5.6E-11
Further LCI results							
air	Sulfur hexafluoride	total	kg	3.1E-10	3.5E-10	4.8E-8	5.7E-8
air	Radon-222	total	kg	3.4E+2	3.4E+2	3.5E+2	3.8E+2

The relative difference of results between one voltage level and the next is very similar for the UCTE, CENTREL and NORDEL countries. The higher losses of the CENTREL in comparison to the UCTE and NORDEL countries show also in the results (see Tab. 15.10 to Tab. 15.12).

Tab. 15.11 Selected LCI results and cumulative energy demand for the UCTE and CENTREL supply mixes at low, medium and high voltage and at busbar

		Name	Unit	electricity, production mix UCTE	electricity, high voltage, production UCTE, at grid	electricity, medium voltage, production UCTE, at grid	electricity, low voltage, production UCTE, at grid	electricity, production mix CENTREL	electricity, high voltage, production CENTREL, at grid	electricity, medium voltage, production CENTREL, at grid	electricity, low voltage, production CENTREL, at grid
		Location		UCTE	UCTE	UCTE	UCTE	CENTREL	CENTREL	CENTREL	CENTREL
		Unit		kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0	0	0	0	0
LCIA results											
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	5.78	5.84	5.90	6.53	10.22	10.33	10.44	11.73
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	4.69	4.74	4.79	5.28	2.10	2.12	2.15	2.41
	cumulative energy demand	renewable energy resources, water	MJ-Eq	0.69	0.70	0.71	0.78	0.17	0.17	0.18	0.20
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.12	0.12	0.12	0.14	0.00	0.00	0.00	0.00
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.07	0.07	0.07	0.09	0.09	0.09	0.09	0.11
LCI results											
resource	Land occupation	total	m2a	9.5E-3	9.6E-3	9.9E-3	1.2E-2	1.8E-2	1.9E-2	1.9E-2	2.3E-2
air	Carbon dioxide, fossil	total	kg	4.5E-1	4.6E-1	4.6E-1	5.1E-1	8.9E-1	9.0E-1	9.1E-1	1.0E+0
air	NMVOC	total	kg	1.0E-4	1.1E-4	1.1E-4	1.2E-4	9.3E-5	9.4E-5	9.5E-5	1.1E-4
air	Nitrogen oxides	total	kg	8.3E-4	8.4E-4	8.5E-4	9.5E-4	1.7E-3	1.8E-3	1.8E-3	2.0E-3
air	Sulphur dioxide	total	kg	1.8E-3	1.8E-3	1.8E-3	2.1E-3	5.4E-3	5.4E-3	5.5E-3	6.2E-3
air	Particulates, < 2.5 um	total	kg	1.2E-4	1.2E-4	1.2E-4	1.4E-4	2.8E-4	2.8E-4	2.9E-4	3.3E-4
water	BOD	total	kg	2.8E-4	2.9E-4	3.0E-4	3.7E-4	1.4E-4	1.4E-4	1.5E-4	2.1E-4
soil	Cadmium	total	kg	1.1E-10	1.1E-10	1.2E-10	1.3E-10	1.1E-10	1.1E-10	1.1E-10	1.3E-10
Further LCI results											
air	Sulfur hexafluoride	total	kg	7.8E-10	8.2E-10	8.0E-8	9.5E-8	7.7E-10	8.1E-10	9.7E-8	1.2E-7
air	Radon-222	total	kg	2.7E+2	2.8E+2	2.8E+2	3.1E+2	1.2E+2	1.2E+2	1.2E+2	1.4E+2

Tab. 15.12 Selected LCI results and cumulative energy demand for the NORDEL supply mix at low, medium and high voltage and at busbar

		Name	Unit	electricity, production mix NORDEL	electricity, high voltage, production NORDEL, at grid	electricity, medium voltage, production NORDEL, at grid	electricity, low voltage, production NORDEL, at grid
		Location		NORDEL	NORDEL	NORDEL	NORDEL
		Unit		kWh	kWh	kWh	kWh
		Infrastructure		0	0	0	0
LCIA results							
	cumulative energy demand	non-renewable energy resources, fossil	MJ-Eq	1.59	1.61	1.64	1.85
	cumulative energy demand	non-renewable energy resources, nuclear	MJ-Eq	2.52	2.55	2.57	2.87
	cumulative energy demand	renewable energy resources, water	MJ-Eq	2.77	2.80	2.83	3.15
	cumulative energy demand	renewable energy resources, wind, solar, geothermal	MJ-Eq	0.18	0.18	0.18	0.20
	cumulative energy demand	renewable energy resources, biomass	MJ-Eq	0.72	0.73	0.74	0.83
LCI results							
resource	Land occupation	total	m2a	1.9E-2	1.9E-2	1.9E-2	2.3E-2
air	Carbon dioxide, fossil	total	kg	1.2E-1	1.2E-1	1.2E-1	1.4E-1
air	NMVOC	total	kg	3.8E-5	3.9E-5	4.0E-5	4.8E-5
air	Nitrogen oxides	total	kg	2.5E-4	2.6E-4	2.6E-4	3.1E-4
air	Sulphur dioxide	total	kg	2.5E-4	2.5E-4	2.7E-4	3.6E-4
air	Particulates, < 2.5 um	total	kg	9.2E-5	9.3E-5	9.5E-5	1.1E-4
water	BOD	total	kg	8.0E-5	8.3E-5	9.1E-5	1.4E-4
soil	Cadmium	total	kg	1.3E-9	1.3E-9	1.3E-9	1.4E-9
Further LCI results							
air	Sulfur hexafluoride	total	kg	4.0E-10	4.4E-10	4.8E-8	5.8E-8
air	Radon-222	total	kg	1.5E+2	1.5E+2	1.5E+2	1.7E+2

15.4 Conclusions

The level of detail of the data used is generally good. The data quality of the power plant technologies and the fuel supply is described in the respective chapters.

The data sets are based on the electricity production of the total power plant parks in the year 2000 and represent therefore no average over several years. This does not account for the fluctuations of meteorological conditions with their influence on the production of hydropower, wind power and photovoltaic. However, rapid changes in the electricity market and the uncertainties and consequences due to war in South Eastern Europe in the nineties do not allow to calculate a meaningful average value. Furthermore, in the context of growing liberalisation of the electricity market, future updates should possibly include models for more company- rather than country-specific electricity mixes.

15.5 References

CENTREL 2001	CENTREL (2001) CENTREL Annual Report 2001, retrieved from www.centrel.org.
EAA 2000	EAA (2000) Environmental profile report for the European aluminium industry April 2000. European Aluminium Association, Brussels.
EURELECTRIC 2001	EURELECTRIC (2001) Statistics and prospects for the European electricity sector (1980-1999, 2000-2020) (Eurprog 2001). Union of the Electricity Industry - EURELECTRIC, Brussels, retrieved from www.eurelectric.org.
Frischknecht et al. 1994	Frischknecht R., Hofstetter P., Knoepfel I., Dones R. and Zollinger E. (1994) Ökoinventare für Energiesysteme. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 1. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut Villigen, Bundesamt für Energie (Hrsg.), Bern.
IEA 2001	IEA (2001) Electricity information 2001. International Energy Agency (IEA), Paris Cedex.
IEA/OECD 2002	IEA/OECD (2002) Energy Statistics of OECD Countries 1999-2000. International Energy Agency, Organisation for Economic Co-Operation and Development, Paris.
NORDEL 2001	NORDEL (2001) Nordel annual report 2000. NORDEL, Oslo, retrieved from www.nordel.org.
UCTE 2001	UCTE (2001) Statistical Yearbook 2000. Union for the Co-ordination of the Trans-mission of Electricity, Berlin, retrieved from www.ucte.org.

16 Abbreviations

BfE	Bundesamt für Energie (Swiss Federal Office of Energy, SFOE)
BfS	Bundesamt für Statistik (Swiss Federal Statistical Office)
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Swiss Agency for the Environment, Forests and Landscape, SAEFL)
cf	Capacity Factor
CAS	Chemical Abstract Service
CED	Cumulative Energy Demand
CENTREL	Central European power association
CFC	Chlorofluorocarbons
CZ-silicon	Czochralski grade silicon
EAWAG	Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz (Swiss Federal Institute for Environmental Science and Technology)
EG silicon	electronic grade silicon
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt (Swiss Federal Laboratories for Materials Testing and Research)
EPDM	Ethylene-propylene rubber
EPFL	Ecole Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology Lausanne)
ESP	Electrostatic Precipitator
ETHZ	Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology Zurich)
FAL	Eidgenössische Forschungsanstalt für Agrarökologie und Landbau (Swiss Federal Research Station for Agroecology and Agriculture)
FGD	Flue Gas Desulphurisation
GHG	Greenhouse Gas
GWP	Greenhouse Warming Potential
H_l	Low Heating Value (Heizwert)
H_u	Upper Heating Value (Brennwert)
HCFC	Hydrochlorofluorocarbons
HDPE	High Density Polyethylene
HLW	High Level radioactive Waste
ILW	Intermediate Level radioactive Waste
ISO	International Organization for Standardization
kWp	kilowatt peak
LCA	Life Cycle Assessment (Ökobilanz)
LCI	Life Cycle Inventory (Sachbilanz)
LCIA	Life Cycle Impact Assessment

LLW	Low Level radioactive Waste
LHV	Lower Heating Value
mc-Si	monocrystalline silicon
MG-silicon	metallurgical grade silicon
nd	no data
NMVOC	Non Methane Volatile Organic Compounds
NORDEL	Nordic Countries power association
ORC	Organic Rancine Cycle
pc-Si	polycrystalline silicon
$PM_{2.5}$	Particles <2.5 µm
PM_{10}	Particles <10 µm
PP	Polypropylene
PSI	Paul Scherrer Institut, Villigen
PVC	Polyvinylchloride
RER	Europe
SKE	Hard Coal Eqivalent
SCR	Selective Catalytic Reduction
SNCR	Selective Non Catalytic Reduction
SoG-Si	solar grade silicon
tkm	ton-kilometre
UCPTE	Union for the Coordination of the Production and Transport of Electricity
UCTE	Union for the Co-ordination of Transmission of Electricity