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Life Cycle Inventories of new CHP systems

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1 Introduction

New systems for combined heat and power generation (CHP) for stationary applications are on the threshold of market introduction (e.g. micro turbines). Other systems such as fuel cells or Stirling engines are in the demonstration phase and pilot plants are being tested. Such systems are of increasing interest because of their prospect for high electrical and high total efficiency.

Several types of small combined heat and power plants with reciprocating engines have been investigated already in Heck (2003). With the inventory of micro gas turbines, fuel cell systems (PEM and SOFC) and stirling motors now also data for further CHP technologies are available within ecoinvent.

Because for CHP-systems the production of chilled water during summertime may be of interest, also a combination of a CHP-system with an absorption chiller is investigated. Further a small diffusion absorption heat pump is investigated due to it's prospect for rising the efficiency of heat production in comparison to a conventional condensing gas boiler. These inventories alow a comparison of the different existing and new technologies for heat, electricity and chilled water production.

Because some of the investigated systems are r not jet available as serial product, the performance data are based on field test results or target values which are expected to be reached with a serial product. These datasets are idicated with the suffix "future".

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. The exergy content is used for the allocation in this project. Allocations based on exergy lead to higher specific requirements and emissions per kWh of electricity compared to 1 kWh heat.

Datasets for operation with natural gas as well as biogas distributed in the regular natural gas network are included. For the Stirling engine wood pellets as fuel is included. The operation of the diffusion absorption heat pump includes a heat dataset for operation with natural gas as well as biogas. For the absorption chiller the dataset "cooling energy, natural gas, at cogen unit with absorption chiller 100 kW" uses heat from a 160 kWel cogeneration unit.

2 Micro gas turbines

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Last changes: 10.12.2007

2.1 Introduction

Micro turbines represent an emerging class of small-scale power generation systems. The basic technology they use is derived from aircraft auxiliary power systems, diesel engine turbochargers and automotive designs. Most micro turbine units are currently designed for continuous-duty operation and use energy recuperation to obtain higher efficiencies.

2.2 Characterisation of material product

Micro turbines are small (output range 28-250 kW), single shaft, recuperated gas turbines. Their technology is relatively advanced and they are commercially available. Their manufacturers include Capstone Turbine Corporation, Ingersoll Rand, Elliott/Bowman and Turbec, most of them with annual production volumes of 10’000-100’000 units.

The waste heat from micro turbines is disposed of only via the exhaust gas, which has a higher temperature (typically 320°C) than the exhaust from a reciprocating engine (typically 150°C). This gives them an advantage over reciprocating engines in CHP applications, especially when higher temperatures are needed (e.g. for steam generation).

Normally, exhaust heat is recovered to preheat fuel or air in order to increase the electrical efficiency. This leads to a larger size of generator but reduces the heat available in co-generation applications.

2.3 Use / application of product

Micro turbines offer good fuel flexibility. They can burn both gaseous and liquid fuels including natural gas, diesel, kerosene and synthetic gases obtained from gasifying coal, biomass, or wastes.

All manufacturers of micro turbines see power generation from renewable energy and biogas sources as a significant market opportunity. Their combustion temperatures of around 900ºC to 1000ºC are sufficiently low to allow these turbines to be tolerant to most compounds potentially present in biogas. Heat can be recovered from the exhaust in co-generation applications.

2.4 System characterisation

Fig. 2.1 shows the system outline of the micro gas turbine modelled here. It is assumed that the turbine is connected to the Swiss and European low-pressure gas network (Faist Emmenegger et al. 2003). Natural gas (Faist Emmenegger et al. 2003) and biogas (Jungbluth et al. 2007) are included as energy carriers to operate the turbine.

Natural gas (or biogas in natural gas quality) is the primary fuel of choice, although other fuels such as propane, diesel or kerosene can be used. Adapted combustors also allow the use of low calorific gases such as landfill gas or digester gas. Fuels with a heating value down to 25% of that of natural gas may be used. However, their efficiency decreases dramatically when the fuel has a methane content below 50%. Micro turbines operated with raw biogas drawn directly from the production site (e.g. an agricultural site or waste water plant) and with liquid fuels such as diesel or kerosene are not considered in this inventory.

A dataset of the heat production corresponding to each electricity dataset is also provided. Electricity production is given in kWh, heat production in MJ. It is assumed that the micro gas turbine is operated in Switzerland (CH). However, the process is applicable also for central European conditions.

The datasets refer to the micro gas turbines available on the market around year 2005. For future developments, higher electrical efficiency are predicted (38-42% electrical efficiency, with ceramic turbine components). These future developments are not considered in the datasets.

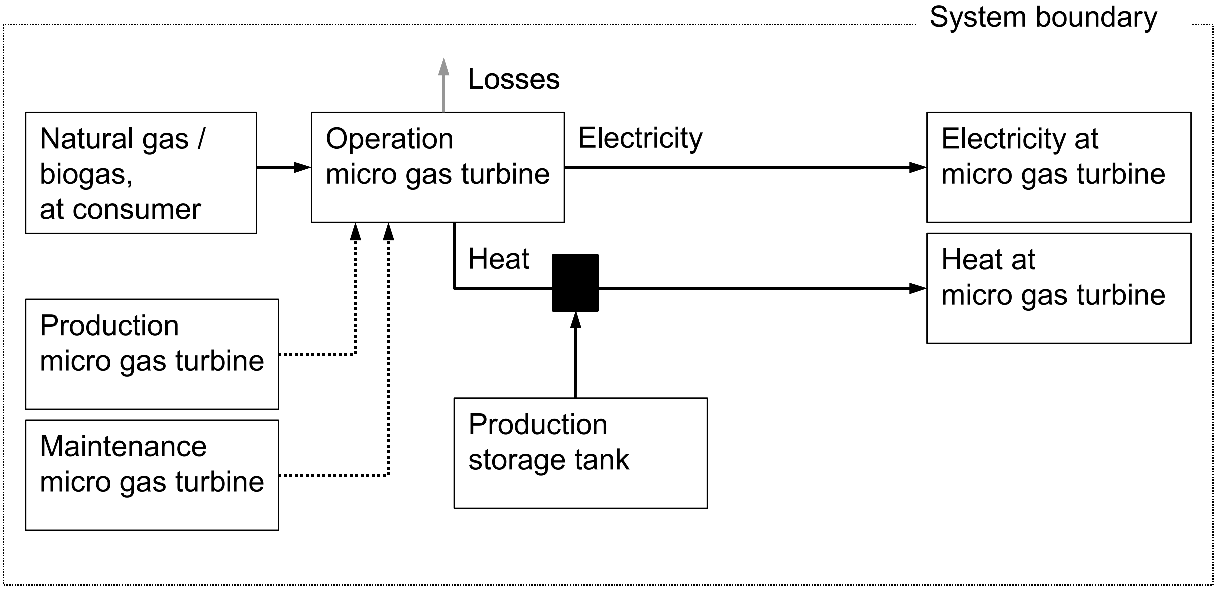

Fig. 2.1 System outline of a micro gas turbine 100 kW_{el}

2.5 Natural gas, burned in micro gas turbine 100 kW_{el}

2.5.1 Technical characteristics

Micro turbines are available with an electrical output of between 28 kW and 250 kW_{el}. The one analysed here has an output of 100 kW_{el}. To increase the electrical efficiency, a recuperator (gas-to-air heat exchanger) preheats the compressed air with the hot exhaust gases exiting from the turbine. As a rule, recuperators increase the electrical efficiency in micro turbines to a value of 26 to 33 percent (Shane 2002), whereas it ranges from 15 to 22 percent without them. The lower value of the electrical efficiency corresponds to small micro turbines (30 kW_{el}), the higher value to larger units (250 kW_{el}).

The electrical efficiency is usually given on the basis of the lower heating value and without a fuel-gas booster. This booster is needed when the turbine is used in a low-pressure gas network. The electrical output power is then reduced by 3 percent (Ingersoll Rand 2004).

The micro turbine analysed here has an electrical efficiency of 30 percent at nominal load and 15°C ambient temperature (fuel-gas booster excluded). Lower ambient temperatures increase the electrical efficiency (+0.15%/°C) and decrease the total efficiency (-0.2%/°C) due to the greater temperature difference between the air intake and the exhaust (Bianci 2005).

During partial load operation, the electrical and total efficiency are reduced. At 50 percent load, a reduction to 78 – 93 percent (Hansen 2004, Bianci 2005) of the nominal electrical efficiency occurs. The total efficiency is reduced to 88 – 97 percent of the nominal value.

During the operation of micro turbines with a power output of 100 kW_{el}, an average electrical efficiency of between 28.9 and 31.5 percent and a total efficiency of between 65 and 79 percent (at 50 to 90 °C water temperature) is measured (Hansen et al. 2004). An average electrical efficiency of 29 percent and a total efficiency of 75 percent are assumed (see Tab 2.1). This assumption implies a system design for base-load operation with a long period at full load and a connection to a low-pressure gas network (fuel-gas booster needed).

Tab 2.1 Electric and thermal efficiencies and losses of a 100 kW_{el} micro gas turbine

Electricity generation	MJ/MJ_{in}	0.29
Heat generation	MJ/MJ_{in}	0.46
Total energy output	MJ/MJ_{in}	0.75
Heat losses	MJ/MJ_{in}	0.25
Waste heat, total *)	MJ/MJ_{in}	0.811
*) Based on HHV; natural gas, CH, low pressure: HHV 40.2 MJ/Nm^3; LHV = 36.5 MJ/Nm^3 and including losses as well as heat generated		

2.5.2 Equipment and maintenance needed

The infrastructure needed is defined by the total operating life and the maintenance interval of the unit. The operating life of a micro turbine lies between 45’000 and 60’000 hours and its maintenance interval between 6000 and 12’000 hours (Turbec 2005, Ohkubo 2006). An operating life of 50’000 hours with five maintenance sessions during this period is assumed.

Typical load factors for micro gas turbines are between 73 and 89 percent of the nominal load (Hansen et al. 2004). An average load factor of 81% is assumed. The fuel consumption is 345 kW at nominal load. Maintenance is needed every 10.1 TJ_{In} of fuel input (five maintenance sessions during the life time), and the operating life of the unit is reached after 50.3 TJ_{In} of fuel input.

Besides the infrastructure of the micro gas turbine, which includes the piping for the sanitary equipment, ventilation, the electrical connections and the planning the piping, a storage tank for hot water is usually needed to ensure good system performance. A storage volume of 7 m^3 is assumed.

The inventory of the storage tank is based on the 10 m^3 tank described in Heck (2003). As in Heck (2003), the operating life of the storage tank is 100'000 hours or 101 TJ$_{In}$ of fuel input.

A gas boiler for peak load and backup is used in order to reach a long operating period at full load. Depending on the variability of the heat requirement, this boiler is able to deliver up to 80% of the peak load. The gas boiler for peak load or backup is not included in this inventory because the system design depends strongly on the specific application.

The infrastructure processes included are summarised in Tab. 2.2.

Tab. 2.2 Equipment and maintenance of micro gas turbines operated with natural gas

Process	Operating life, interval	Amount
Micro gas turbine 100kWe	50'000 h	1.99 E-8 units/MJ$_{in}$
Maintenance of micro gas turbine 100kWe	5 times per 50'000 h	9.95 E-8 units/MJ$_{in}$
Storage 10'000 l , *)	100'000 h	8.25 E-9 units/MJ$_{in}$
*) For 7 m^3 storage size, 0.83 units are used.		

2.5.3 Energy and auxiliaries usage

Natural gas consumption

The technical characteristics described in Section 2.5.1 specify the use of natural gas from the Swiss low-pressure gas network. According to Faist Emmenegger et al. (2003), the gas has a lower heating value of 36.5 MJ/Nm^3 and a higher heating value of 40.2 MJ/Nm^3.

Lubricant consumption

The lubricant consumption varies between 0 and 3 litres per 6000 operating hours (Capstone 2006, Turbec 2005). Turbine designs with air bearings do not require any lubrication. For earlier designs, the lubricant consumption was up to 9 litres per 6000 operating hours. A lubricant consumption of 3 litres per 6000 operating hours as given in Turbec (2005) is used here, which equals 0.5 mg/MJ$_{In}$ (calculated with an average load factor of 81%).

2.5.4 Emissions to air

Like larger turbines, micro turbines have an advantage over reciprocating engines in terms of emissions. They do not need a catalytic converter for reducing these due to their low emission level of NO_X and CO.

The CO_2 emissions for natural gas consumed from the Swiss gas network are 56 g/MJ$_{In}$ (Faist Emmenegger et al. 2003).

The emissions of nitrogen oxides at nominal load are reduced to a level of 9-15 ppm$_V$ (@ 15% O_2), equivalent to 19-32 mg/MJ$_{In}$ in newer micro gas turbines. Depending on their operating efficiency, the emission level achieved can also be significantly higher. Nitrogen oxide emissions usually lie between 16 and 63 mg/MJ$_{In}$.

Carbon monoxide emissions are low when good combustion is achieved. This may not be the case under partial load conditions below 75% of nominal power. Under such conditions, carbon monoxide may rise to levels of 1 g/MJ$_{In}$ or more. It is assumed that partial load operation is avoided for reasons of economy (system design for a base load with a long period at full load). Under this assumption, high carbon monoxide emissions will only increase during start-up or shutdown. Average carbon monoxide emissions of 28 mg/MJ$_{In}$ are consequently used here.

The behaviour of hydrocarbon emissions is similar to that of the carbon monoxide emissions. Under normal operating conditions, these are very low (or undetectable). An average emission level of

6 mg/MJ_{In} of hydrocarbons is used here. Only values for total hydrocarbon emissions (including methane) are available. As in (Heck 2003), it is assumed that 90 percent of the hydrocarbon emissions are emitted as methane (the rest is counted as NMVOC). A similar value is used for the large gas turbines discussed in Faist Emmenegger et al. (2003), where 82 percent of the hydrocarbon emissions are emitted as methane.

Only a few available sources state the particulate emissions of micro gas turbines. According to these sources, the emission level is estimated at 0.5 mg/MJ_{In}. This value corresponds to the emission factor used for large gas turbines in Krewitt et al. (2004) and large natural-gas power plants in Faist Emmenegger et al. (2003) but is clearly higher compared to that used by Heck (2003) for engine-driven CHP plants (0.15 mg $PM2.5/MJ_{In}$). As in Heck (2003), it is assumed that these emissions are emitted as PM2.5 particles.

No data are available for nitrous oxide emissions from micro gas turbines. N_2O emissions are estimated to be similar to those of the large gas turbines discussed in Faist Emmenegger et al. (2003). An N_2O emission factor of 1 mg N_2O/MJ_{In} is therefore applied here.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied.

The emission values used for operation with natural gas are summarised in Tab. 2.3.

Tab. 2.3 Emissions to air of micro gas turbines operated with natural gas

NOx mg/MJ_{In}	CO mg/MJ_{In}	THC mg/MJ_{In}	Particulates mg/MJ_{In}	SO_2 mg/MJ_{In}	Source
32	18	6	-	-	Turbec (2005), Bianci (2005)
6	0-640 *)	-	-	-	Perego and Belloni (2005)
10-19 (26)	(41)	(42)	(0.4)	-	Capstone (2006), **)
19	19-63	-	-	-	Ingersoll Rand (2003, 2004)
53	33	-	-	-	Elliot Microturbines (2005)
18-64	12-1150 *)	>9-680 *)	-	-	Hansen et al. (2004)
16-44	9-46	< 5	-	-	Goldstein et al. (2003)
14	8	< 5	-	-	Olausson (1999)
21-220	23-36	-	0.46-3	0.23-2	Nadal (1997), ***)
32	**28**	**6 ****)**	**0.5 (PM 2.5)**	**0.55**	**Used in this inventory**
116	233	-	-	116	Emission limit LRV (2005), *****)

*) Higher value at 50% part load
**) Values in brackets for models without heat recovery dated from 2004 spec. sheet
***) Higher values show a micro gas turbine with only 18% electrical efficiency
****) Of this, 5.4 mg/MJ_{In} as CH4 and 0.6 mg/MJ_{In} as NMVOC
*****) Emission limit in Switzerland for gas turbines <40MW_{th}; NOx, SO_2: 120 mg/Nm^3; CO: 240 mg/Nm^3

2.5.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- Heat, natural gas, allocation exergy, at micro gas turbine 100 kWe
- Electricity, natural gas, allocation exergy, at micro gas turbine 100 kWe

Various allocation concepts may be applied and are discussed in Heck (2003). In this project, the exergy content is applied. Allocations based on exergy lead to higher specific requirements and emissions per kWh electricity compared to 1 kWh heat. The allocation factors are determined according to the calculation presented in Heck (2003). Tab. 2.4 summarises the resulting allocation factors and underlying assumptions.

Tab. 2.4 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	29 %	46 %	75 %
Exergy factor *)	1.000	0.170	-
Allocation factor	78.8 %	21.2 %	100.0 %
*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production			

2.5.6 Data quality considerations

Tab. 2.5 shows the multi-output process raw data and data-quality indicators of the inventory of natural gas, burned in micro gas turbine 100 kW_{el}.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements of a particular engine in operation, but merely represents information available from the manufacturers of such engines.

Tab. 2.5 Multi-output process raw data of natural gas, burned in micro gas turbine 100 kWel

	Name	Location	InfrastructureProcess	Unit	natural gas, burned in micro gas turbine 100kWe	UncertaintyType	StandardDeviation95%	GeneralComment	heat, natural gas, allocation exergy, at micro gas turbine 100kWe	electricity, natural gas, allocation exergy, at micro gas turbine 100kWe
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, natural gas, allocation exergy, at micro gas turbine 100kWe	CH	0	MJ	4.60E-1				100	0
	electricity, natural gas, allocation exergy, at micro gas turbine 100kWe	CH	0	kWh	8.06E-2				0	100
technosphere	micro gas turbine 100kWe	CH	1	unit	1.99E-8	1	1.14	(2,3,2,1,1,4); uncertainty of life time	21.2	78.8
	maintenance micro gas turbine 100kWe	CH	0	unit	9.95E-8	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	21.2	78.8
	storage 10'000 l	RER	1	unit	8.25E-9	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	natural gas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	21.2	78.8
	lubricating oil, at plant	RER	0	kg	5.00E-7	1	1.14	(2,3,2,1,1,4); company data	21.2	78.8
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	5.50E-7	1	1.31	(4,3,2,1,1,5); calculated from oil input	21.2	78.8
emission air, high population density	Carbon dioxide, fossil	-	-	kg	5.60E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	21.2	78.8
	Carbon monoxide, fossil	-	-	kg	2.80E-5	1	5.02	(2,3,2,1,1,4); estimate based on different references	21.2	78.8
	Dinitrogen monoxide	-	-	kg	1.00E-6	1	1.94	(4,5,3,1,4,5); value for large gas power plants used as approximation	21.2	78.8
	Methane, fossil	-	-	kg	5.40E-6	1	1.62	(4,3,2,1,1,5); estimate based on few references	21.2	78.8
	Nitrogen oxides	-	-	kg	3.20E-5	1	1.53	(2,3,2,1,1,4); estimate based on different references	21.2	78.8
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	6.00E-7	1	1.62	(4,3,2,1,1,5); estimate based on few references	21.2	78.8
	Particulates, < 2.5 um	-	-	kg	5.00E-7	1	3.34	(4,4,3,2,4,5); value for large gas power plants used as approximation	21.2	78.8
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	21.2	78.8
	Heat, waste	-	-	MJ	8.11E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	21.2	78.8

2.6 Biogas gas, burned in micro gas turbine 100 kW_{el}

2.6.1 Technical characteristics

Micro gas turbines can be operated with biogas. Biogas with a heating value of at least 25% of that for natural gas may be used. The gas should have a methane content of more than 50 vol-% and the H_2S content must be below 400 ppm_V. According to Capstone (2006), the electrical efficiencies achieved for landfill gas and digester gas are similar to those for units operated with natural gas.

Only biogas distributed in the regular natural gas network is considered. This biogas has a quality similar to natural gas. The methane content must be at least 96 vol-%.

Under these conditions, operation of the micro gas turbine with biogas is similar to that with natural gas (see Section 2.5.1). For micro gas turbines operated with refined biogas, an average electrical efficiency of 29 percent and a total efficiency of 75 percent is assumed (see Tab. 2.6). This assumption implies a system design for base-load operation during a long period at full load and a connection to a low-pressure gas network (fuel-gas booster needed).

Tab. 2.6 Electric and thermal efficiencies and losses of a 100 kW_{el} micro gas turbine

Electricity generation	MJ/MJ_{in}	0.29
Heat generation	MJ/MJ_{in}	0.46
Total energy output	MJ/MJ_{in}	0.75
Heat losses	MJ/MJ_{in}	0.25
Waste heat, total *)	MJ/MJ_{in}	0.817
*) Based on HHV; biogas, CH, high pressure: HHV 38.146 MJ/Nm^3; LHV = 34.450 MJ/Nm^3 and including losses as well as heat generated		

2.6.2 Equipment and maintenance needed

The infrastructure needed is identical to that of the engines operated with natural gas presented in Section 2.5.2 (Tab. 2.2). An operating life of 50’000 hours with five maintenance sessions during this period is assumed. Maintenance is needed every 10.1 TJ_{In} of fuel input and the full operating life of the unit is reached after 50.3 TJ_{In} of fuel input. As in the unit operated with natural gas, a storage tank volume of 7 m^3 is assumed; this has to be replaced after every 101 TJ_{In} of fuel input.

2.6.3 Energy and auxiliaries usage

Biogas consumption

The distribution requirements (energy, leakages) are similar to those of natural gas. Only the emissions differ in their composition due to the different composition of biogas compared to natural gas. The dataset “methane, 96 vol-%, from biogas, low pressure, at consumer” is used as the process input for the micro gas turbine. According to Jungbluth et al. (2007), the gas has a lower heating value of 34.45 MJ/Nm^3 and a higher heating value of 38.15 MJ/Nm^3.

An average load factor of 81% is assumed as defined for operation with natural gas.

Lubricant consumption

The lubricant consumption for biogas operation is identical to that for operation with natural gas. A value of 0.5 mg/MJ_{In} is used in the inventory.

2.6.4 Emissions to air

The CO_2 emissions (biogenic) are calculated on the basis of the carbon content of the biogas mix. The value presented in Tab. 2.7 also takes into account the carbon emitted in the form of CO, CH_4 and NMVOC.

According to the biogas composition presented in Jungbluth et al. (2007), the refined biogas has a slightly lower nitrogen content than natural gas. Because a large part of the nitrogen oxide emissions originate from the nitrogen in the combustion air, identical emission factors are used. An NO_X emission factor of 32 mg N_2O/MJ_{In} is applied here.

Micro gas turbines operated with raw biogas often show higher levels of carbon monoxide and hydrocarbon emissions. The gas compositions of refined biogas and natural gas are similar. Identical emission factors for carbon monoxide (28 mg/MJ_{In}) and hydrocarbons (6 mg/MJ_{In}) are therefore assumed for both biogas and natural gas (see Section 2.5.4). Only values for total hydrocarbon emissions (including methane) are available. As in (Heck 2003), it is assumed that 90 percent of the hydrocarbon emissions are emitted as methane (5.4 mg/MJ_{In}) and the rest as NMVOC (0.6 mg/MJ_{In}).

No data are available for the particulate emissions of micro gas turbines operated with refined biogas. It is assumed that the emission level is similar to that for operation with natural gas (see Section 2.5.4) and an emission factor of 0.5 mg/MJ_{In} is therefore applied. As in Heck (2003), it is assumed that these particles are emitted as PM2.5.

No data are available for the nitrous oxide emissions of micro gas turbines. These N_2O emissions are estimated to be similar to those of the large gas turbines discussed in Faist Emmenegger et al. (2003). An N_2O emission factor of 1 mg N_2O/MJ_{In} is applied here.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas. The H_2S content in odorated natural gas is similar to that of the biogas presented in Jungbluth (2007). According to Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied.

Tab. 2.7 CO_2 emissions and carbon balance

	Emission factor	Carbon content	Share
Biogas input	-	524,992.3 mg C / Nm^3 15,239.3 mg C / MJ_{In}	100.00 %
Carbon dioxide, biogenic	55,778.3 mg/MJ_{In}	15,222.8 mg C / MJ_{In}	99.89 %
Carbon monoxide, biogenic	28.0 mg/MJ_{In}	12.0 mg C / MJ_{In}	0.08 %
Methane, biogenic	5.4 mg/MJ_{In}	4.0 mg C / MJ_{In}	0.03 %
NMVOC *)	0.6 mg/MJ_{In}	0.5 mg C / MJ_{In}	0.00 %
*) Carbon content calculated as C_5H_{12} (Pentane)			

2.6.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, biogas, allocation exergy, at micro gas turbine 100 kWe
- electricity, biogas, allocation exergy, at micro gas turbine 100 kWe

Various allocation concepts may be applied and are discussed in Heck (2003). In this project, the exergy content is applied. Allocation based on exergy leads to higher specific requirements and emissions per kWh of electricity compared to 1 kWh of heat. The allocation factors are determined according to the calculation presented in Heck (2003). Tab. 2.8 summarises the resulting allocation factors and underlying assumptions.

Tab. 2.8 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	29 %	46 %	75 %
Exergy factor *)	1.000	0.170	-
Allocation factor	78.8 %	21.2 %	100.0 %
*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production			

2.6.6 Data quality considerations

Tab. 2.9 shows the multi-output process raw data and data-quality indicators of the inventory of biogas, burned in micro gas turbine 100 kW_{el}.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements of a particular engine in operation, but merely represents information available from the manufacturer of such engines.

Tab. 2.9 Multi-output process raw data of biogas, burned in micro gas turbine 100 kWel

	Name	Location	InfrastructureProcess	Unit	biogas, burned in micro gas turbine 100kWe	UncertaintyType	StandardDeviation95%	GeneralComment	heat, biogas, allocation exergy, at micro gas turbine 100kWe	electricity, biogas, allocation exergy, at micro gas turbine 100kWe
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, biogas, allocation exergy, at micro gas turbine 100kWe	CH	0	MJ	4.50E-1				100	0
	electricity, biogas, allocation exergy, at micro gas turbine 100kWe	CH	0	kWh	8.33E-2				0	100
technosphere	micro gas turbine 100kWe	CH	1	unit	1.99E-8	1	3.02	(2,3,2,1,1,4); uncertainty of life time	21.2	78.8
	maintenance micro gas turbine 100kWe	CH	0	unit	9.95E-8	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	21.2	78.8
	storage 10'000 l	RER	1	unit	8.25E-9	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	21.2	78.8
	lubricating oil, at plant	RER	0	kg	5.00E-7	1	1.14	(2,3,2,1,1,4); company data	21.2	78.8
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	5.50E-7	1	1.31	(4,3,2,1,1,5); calculated from oil input	21.2	78.8
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	5.58E-2	1	1.07	(2,nA,nA,nA,1,nA); calculated from composition of biogas	21.2	78.8
	Carbon monoxide, biogenic	-	-	kg	2.80E-5	1	5.07	(2,3,2,1,3,4); estimate based on different references	21.2	78.8
	Dinitrogen monoxide	-	-	kg	1.00E-6	1	1.94	(4,5,3,1,4,5); value for large natural gas power plants used as approximation	21.2	78.8
	Methane, biogenic	-	-	kg	5.40E-6	1	1.68	(4,3,2,1,3,5); estimate based on few references	21.2	78.8
	Nitrogen oxides	-	-	kg	3.20E-5	1	1.59	(2,3,2,1,3,4); estimate based on different references	21.2	78.8
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	6.00E-7	1	1.68	(4,3,2,1,3,5); estimate based on few references	21.2	78.8
	Particulates, < 2.5 um	-	-	kg	5.00E-7	1	3.34	(4,4,3,2,4,5); value for large natural gas power plants used as approximation	21.2	78.8
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.22	(2,nA,nA,nA,3,nA); approximation with data from natural gas network	21.2	78.8
	Heat, waste	-	-	MJ	8.17E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	21.2	78.8

2.7 Manufacture of a 100 kW_{el} micro gas turbine

2.7.1 Technical characteristics

The infrastructure dataset of the micro gas turbine includes the most important materials used for its production, the transport of these materials and the energy needed for its production and engineering.

Micro turbines of the same power capacities are typically 40 percent smaller than diesel engines, a micro turbine occupying 45 percent of the footprint of a typical diesel engine. The production process involves various steps including raw material cutting, casting, machining and welding. Steel is the principal material used, others being high-temperature alloys (Ni-Alloy), stainless steel (compressor, recuperator), copper and aluminium.

2.7.2 Manufacturing site

According to Capstone (2001), the production facilities for an annual production of 15-20’000 units (with an electrical power of 30-65 kW_{el}) cover 17,500 m^2 of floor space (offices, production and storage). No detailed information is available on the building and other infrastructures. It is assumed that 8500 m^2 of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 27’000 m^3. The service life of the buildings is assumed to be 50 years. For the calculations, annual production of 8’000 units with an electrical power of 100 kW_{el} is assumed (original data scaled by weight according to Fig. 2.2 to 100 kW_{el}). Each unit bears the environmental burdens of 0.021 m^2 of the building hall and 0.068 m^3 of the multi-storey building. Other infrastructures are neglected.

The land use of the production facilities is approximated with the assumption that the sealed area is similar to the total floor area of 17,500 m^2. This assumption implies that a large part of the area is only one storey high (production and storage halls). The whole site is classified as an “industrial built-up area” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of 0.044 m^2 of land transformation and 2.19 m^2 a of land occupation.

2.7.3 Raw materials, energy and auxiliaries

The amount of raw materials and energy used for the production of the micro gas turbine is derived from an inventory of a 250 kW_{el} micro gas turbine (Nadal 1997). The data presented in Fig. 2.2 from various manufacturers show an almost linear dependence between nominal electrical power and the weight of the micro co-generation unit (Capstone 2006, Elliot Micro turbines 2005, Ingersoll Rand 2003, Ingersoll Rand 2004, Turbec 2005). These values comprise only the co-generation unit itself but no auxiliary system such as ducting, air intake and chimney. The total mass of material given in Nadal (1997) also includes these auxiliary systems and is therefore considerably higher.

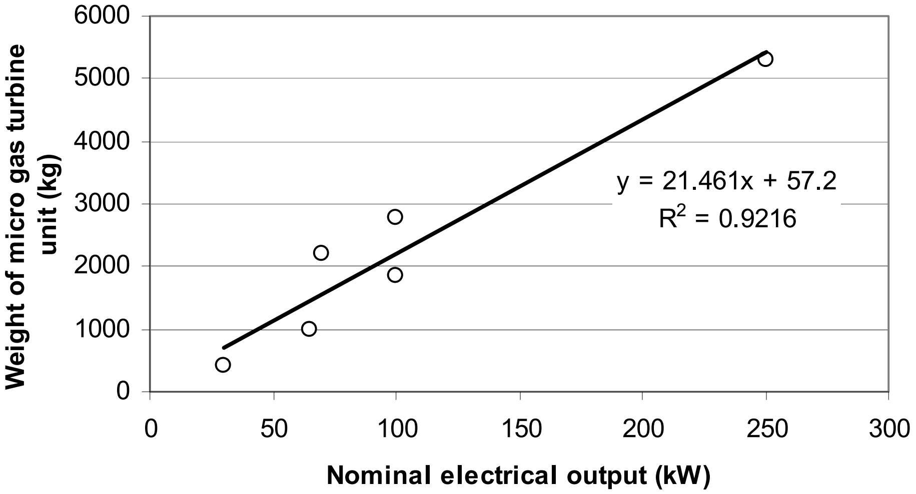

Fig. 2.2 Weight and nominal electrical power output of different micro gas turbine units

The material end energy data presented in Nadal (1997) are scaled down to a 100 kW_{el} micro gas turbine according to Fig. 2.2. The data used for the inventory are shown in Tab. 2.10.

Nadal (1997) does not include the fuel and electricity used within the buildings (only some process energy). For each micro gas turbine unit (100 kW_{el}), an additional energy requirement for heating and electricity amounting to 15.3 GJ of heat (natural gas, at industrial furnace >100kW) and 2.12 MWh of electricity (medium voltage, production UCTE, at grid) is included. The amount used is based on the specific energy requirement per kg product of a similar production site (Viessmann 2005).

The material and energy required for the foundations is modelled according to the dataset of the 10 m^2 foundations described in Heck (2003). Foundations of 4 m^2 are needed for the 100 kW_{el} micro gas turbine.

No data are available for the water consumption required for manufacturing micro gas turbines. The amount used (see Tab. 2.10) is based on the specific water requirement of 1.22 litre per kg product for a similar production site (Viessmann 2005).

Additional energy is consumed for planning and engineering. Experience from similar projects suggests that 400 working hours of planning and engineering are needed for a 100 kW_{el} gas turbine unit. On the basis of data from Aebischer and Catenazzi (2006), a specific energy consumption of 15 MJ/h of heat (light fuel oil, burned in a 100-kW boiler, non-modulating) and 2 kWh/h of electricity (low voltage, at grid, CH) is used to calculate the energy requirement.

The planning and engineering of a micro gas turbine needs more on-site visits than an average engineering project. Professional experience suggests that the transport requirements range around 1-3 km per working hour for an average engineering project. Heck (2003) gives a transport distance of 5600 pkm for planning and engineering a 160 kW_{el} co-generation unit. It is assumed that the construction site is visited 10 times and the distance of 200 km (return trip) for each visit is covered by car.

Tab. 2.10 Raw materials, energy and auxiliaries of the manufacture of a 100 kW$_{el}$ micro gas turbine

	Unit	Nadal (1997)	Used in this study	
Size of micro gas turbine (nominal electrical power)	**-**	**250 kW$_{el}$**	**100 kW$_{el}$**	
Reinforcing steel, at plant	kg	3090	1236	R
Steel, low-alloy, at plant	kg	5090	2036	R
Chromium steel 18/8, at plant	kg	1110	444	R
Copper, at regional storage	kg	300	120	R
Aluminium, production mix, wrought alloy, at plant	kg	170	68	R
Iron-nickel-chromium alloy, at plant	kg	90	36	R
Polyethylene, HDPE, granulate, at plant	kg	150	30 **)	I
Polyvinylchloride, at regional storage	kg		30 **)	I
Sheet rolling, steel	kg	9290	3272 ***)	
Sheet rolling, chromium steel	kg		444 ***)	
Sheet rolling, aluminium	kg	170	68	
Welding, arc, steel	m	10	4	
Transport, transoceanic freight ship	tkm	80000	32000	
Transport, lorry >28t, fleet average	tkm	2000	800	
Engine installation: transport, lorry >28t, fleet average	tkm	1200 *)	480	
Water for manufacturing (unspecified natural origin)	m3	Not available	4.88	W
Construction work, cogen unit 160kWe (10 m^2 foundation)	Unit	Not available	0.4	
Heating production site: natural gas, at industrial furnace >100kW	MJ	Not available	15300	
Electricity production site: medium voltage, production UCTE, at grid	kWh	Not available	2120	
Heating engineering services: light fuel oil, burned in boiler 100kW, non-modulating	MJ	Not available	6000	
Electricity engineering services: low voltage, at grid, at grid, CH	kWh	Not available.	800	
Transport engineering: transport, passenger car, CH	pkm	Not available	2000	
Dismantling: R = Recycling; I = Disposal in municipal incineration plant; W = Disposal in waste-water plant *) Value of 20 t.hr in Nadal (1997) equals a transport of 1200 tkm **) Assumption that 50% of the plastic material is PE and 50% PVC ***) Differentiation according to material input				Dismantling

2.7.4 Emissions to air and water

Emissions to air are included in the unit processes used (e.g. heating or transport processes). No further emissions are included. An average wastewater treatment process is used for wastewater disposal due to a lack of data on water emissions from manufacturing. It is assumed that all the fresh water used is disposed of as waste water via a wastewater treatment plant.

2.7.5 Dismantling

After their operating life, micro gas turbines are dismantled and the materials recycled or disposed of. It is assumed that all metals are recycled. No environmental burdens from dismantling and recycling are included for these materials (cut-off). For plastic materials, final disposal in a municipal incineration plant is assumed. The amount and type of disposal of the various materials is indicated in Tab. 2.10. The value used in Tab. 2.11 includes the water content of the waste.

2.7.6 Data quality considerations

Tab. 2.11 shows the unit process raw data and data-quality indicators of the manufacture and disposal of a micro gas turbine with 100 kW$_{el}$ of nominal electrical power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for various additional processes which are not covered in the data source. Large uncertainties exist for the transport distances. Other types of energy use are also possible for this process.

Tab. 2.11 Unit process raw data of the manufacture of a 100 kW_{el} micro gas turbine

	Name	Location	InfrastructureProcess	Unit	micro gas turbine 100kWe	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	micro gas turbine 100kWe	CH	1	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	1.24E+3	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	steel, low-alloyed, at plant	RER	0	kg	2.04E+3	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	chromium steel 18/8, at plant	RER	0	kg	4.44E+2	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	copper, at regional storage	RER	0	kg	1.20E+2	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	aluminium, production mix, wrought alloy, at plant	RER	0	kg	6.80E+1	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	iron-nickel-chromium alloy, at plant	RER	0	kg	3.60E+1	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted
	polyethylene, HDPE, granulate, at plant	RER	0	kg	3.00E+1	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for material type
	polyvinylchloride, at regional storage	RER	0	kg	3.00E+1	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for material type
	sheet rolling, steel	RER	0	kg	3.27E+3	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for process used
	sheet rolling, chromium steel	RER	0	kg	4.44E+2	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for process used
	sheet rolling, aluminium	RER	0	kg	6.80E+1	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for process used
	welding, arc, steel	RER	0	m	4.00E+0	1	1.35	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for material type
	construction work, cogen unit 160kWe	RER	1	unit	4.00E-1	1	3.12	(2,4,3,2,3,5); data from 160 kWel engine cogen plant adapted
	transport, transoceanic freight ship	OCE	0	tkm	3.20E+4	1	2.12	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for material type
	transport, lorry >28t, fleet average	CH	0	tkm	1.28E+3	1	2.12	(2,4,3,2,3,5); data from 250kWel plant adapted, assumption for material type
	transport, passenger car	CH	0	pkm	2.00E+3	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.53E+4	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.00E+3	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	2.12E+3	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	electricity, low voltage, at grid	CH	0	kWh	8.00E+2	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	3.00E+1	1	1.35	(2,4,3,2,3,5); approximation for disposal of plastic parts
	disposal, building, polyvinylchloride products, to final disposal	CH	0	kg	3.00E+1	1	1.35	(2,4,3,2,3,5); approximation for disposal of plastic parts
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	4.88E+0	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	6.80E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
	building, hall, steel construction	CH	1	m2	2.10E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
resource, in water	Water, unspecified natural origin	-	-	m3	4.88E+0	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	2.19E+0	1	1.65	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, from unknown	-	-	m2	4.40E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, to industrial area, built up	-	-	m2	4.40E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
emission air, high population density	Heat, waste	-	-	MJ	1.05E+4	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

2.8 Maintenance of a 100 kW_{el} micro gas turbine

2.8.1 Technical characteristics

The dataset representing the maintenance of the micro gas turbine includes the estimated material use and transport services for these activities.

Micro turbines have the potential for a low maintenance requirement. The units have easily serviceable components, and the regular (about every 8000 hr) maintenance usually requires no more than simple changes of the air and gas filters. Ignitors or spark plugs, thermocouples and fuel injectors are replaced at every second maintenance period. An overhaul of the turbine is required after about 30'000 h (Shane, 2002).

2.8.2 Raw materials, energy and auxiliaries

According to Hansen et al. (2004), the cost for maintenance is 15 €/MWh_{el}. For a service interval of 8300 operating hours (five maintenance jobs during the operating life), the maintenance amounts to 5% of the installation costs. It is assumed that 20% of the maintenance costs are material costs. The amount of material required for maintenance is estimated to be 1% of the total plant weight for an average maintenance (= 40 kg).

It is assumed that the service personnel travels 200 km for each maintenance job, which takes between 2 h (inspection) and 8 h (overhaul, every 30'000 h), according to Turbec (2005).

2.8.3 Emissions to air

Emissions to air are included in the unit processes used (e.g. transport processes). No further process-related air emissions occur.

2.8.4 Data quality considerations

Tab. 2.12 shows the unit process raw data and data-quality indicators of the maintenance of a micro gas turbine with 100kW_{el} of nominal electrical power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. The inventory is based on only a rough estimate for the process. Large uncertainties exist for the transport distances and the amount of material used. In general, therefore, the data quality is not very reliable.

Tab. 2.12 Unit process raw data for the maintenance of a 100 kW_{el} micro gas turbine

	Name	Location	InfrastructureProces	Unit	maintenance micro gas turbine 100kWe	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				unit			
product	maintenance micro gas turbine 100kWe	CH	0	unit	1			
technosphere	micro gas turbine 100kWe	CH	1	unit	1.00E-2	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on mainenance costs
	transport, passenger car	CH	0	pkm	2.00E+2	1	2.14	(4,5,n.A.,n.A.,1,5); estimated

2.9 Cumulative results and interpretation

2.9.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Multi-output process “natural gas, burned in micro gas turbine 100 kW$_{el}$”

The major part of the NMVOC (98%), nitrogen oxide (43%) and particulate < 2.5um emissions (49%) and the cumulative energy demand (fossil: 99%, nuclear: 69%) are caused by the natural gas used for operation. The major part of the carbon dioxide (87%), nitrogen oxide (55%) and particulate < 2.5um emissions (33%) are caused by direct emissions from operation. The manufacture of the micro gas turbine is for the particulate < 2.5um air emissions (17%), cadmium soil emissions (18%), the land use (13%) and the cumulative nuclear energy demand (27%) of importance. Tab. 2.13 shows selected LCI results and cumulative energy demands for electricity and heat production with a micro gas turbine. The results depend significantly on the chosen allocation method.

Multi-output process “biogas, burned in micro gas turbine 100 kW$_{el}$”

The major part of the fossil carbon dioxide (98%), NMVOC (88%), nitrogen oxide (28%) and particulate < 2.5um emissions (56%) and the cumulative energy demand (biomass: 97%, fossil: 98%, nuclear: 99%) are caused by the refined biogas used for operation. The major part of the nitrogen oxide (70%) are caused by direct emissions from operation. A smaller part of the NMVOC (9%) and particulate < 2.5um emissions (28%) are caused by direct emissions from operation. The manufacture of the micro gas turbine is for the particulate < 2.5um air emissions (14%) of importance. Tab. 2.13 shows selected LCI results and cumulative energy demands for electricity and heat production with a micro gas turbine. The results depend significantly on the chosen allocation method.

Process “micro gas turbine 100 kW$_{el}$”

The major part of the fossil carbon dioxide (50%), NMVOC (50%), nitrogen oxide (50%) and particulate < 2.5um emissions (76%) and the cumulative energy demand (fossil: 50%, nuclear: 37%) are caused by the steel, stainless steel and nickel alloy used for the micro gas turbine. The electricity used for the production of the micro gas turbine makes up 32% of the cumulative nuclear energy demand. Tab. 2.13 shows selected LCI results and cumulative energy demands for the manufacture of a 100 kW$_{el}$ micro gas turbine.

Tab. 2.13 shows selected LCI results and the cumulative energy demand for electricity and heat production with micro gas turbines. The results depend significantly on the allocation method chosen.

Tab. 2.13 Selected LCI results and the cumulative energy demand of micro gas turbines

Ecocat	**Ecosubcat**	**Name**	**Name**	heat, natural gas, allocation exergy, at micro gas turbine 100kWe	heat, biogas, allocation exergy, at micro gas turbine 100kWe	electricity, natural gas, allocation exergy, at micro gas turbine 100kWe	electricity, biogas, allocation exergy, at micro gas turbine 100kWe	micro gas turbine 100kWe	maintenance micro gas turbine 100kWe
			Location	CH	CH	CH	CH	CH	CH
			Unit	MJ	MJ	kWh	kWh	unit	unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	5.57E-01	1.17E-01	1.18E+01	2.32E+00	2.11E+05	2.69E+03
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	1.73E-03	8.44E-02	3.28E-02	1.69E+00	4.68E+04	5.41E+02
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	7.34E-07	4.09E-07	1.55E-05	8.18E-06	2.37E-01	3.91E-03
	water	renewable energy resources, water	MJ-Eq	8.88E-04	1.77E-02	1.74E-02	3.53E-01	1.16E+04	1.30E+02
	biomass	renewable energy resources, biomass	MJ-Eq	1.54E-04	6.78E-04	3.08E-03	1.34E-02	2.14E+03	2.29E+01
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	3.09E-05	2.83E-04	6.05E-04	5.63E-03	7.07E+02	7.62E+00
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	3.95E-07	9.25E-06	7.64E-06	1.85E-04	1.06E+01	1.17E-01
selected LCI results	resource	land occupation	m2a	5.00E-05	1.59E-04	1.01E-03	3.14E-03	6.85E+02	8.29E+00
	air	CO2, fossil	kg	2.96E-02	6.85E-03	6.27E-01	1.36E-01	1.45E+04	1.82E+02
	air	NMVOC	kg	1.78E-05	3.29E-06	3.77E-04	6.52E-05	9.14E+00	1.48E-01
	air	nitrogen oxides	kg	2.68E-05	2.17E-05	5.65E-04	4.32E-04	3.83E+01	4.58E-01
	air	sulphur dioxide	kg	1.41E-05	1.39E-05	2.96E-04	2.74E-04	6.75E+01	7.35E-01
	air	particulates, <2.5 um	kg	7.40E-07	8.79E-07	1.48E-05	1.68E-05	1.27E+01	1.33E-01
	water	BOD	kg	2.88E-06	2.22E-06	5.90E-05	4.25E-05	2.32E+01	3.37E-01
	soil	cadmium	kg	1.84E-13	9.86E-13	3.52E-12	1.94E-11	3.33E-06	4.96E-08

2.10 Conclusions

The LCI results show that the fuel and the emissions from the operation of the micro gas turbine are for most elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 2.13) the production of the infrastructure is important and can not be neglected.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are clearly higher with the use of biogas.

2.11 Appendices: EcoSpold Meta Information

Tab. 2.14 EcoSpold meta information for co-generation with a 100 kW$_{el}$ micro gas turbine

ReferenceFunction	Name	micro gas turbine 100kWe	natural gas, burned in micro gas turbine 100kWe	biogas, burned in micro gas turbine	maintenance micro gas turbine 100kWe
Geography	Location	CH	CH	CH	CH
ReferenceFunction	InfrastructureProcess	1	0	0	0
ReferenceFunction	Unit	unit	MJ	MJ	unit
DataSetInformation	Type	1	5	5	1
	Version	2.0	2.0	2.0	2.0
	energyValues	0	0	0	0
	LanguageCode	en	en	en	en
	LocalLanguageCode	de	de	de	de
DataEntryBy	Person	72	72	72	72
	QualityNetwork	1	1	1	1
ReferenceFunction	DataSetRelatesToProduct	1	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials and for the engine delivery and installation on the site.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes an estimation for materials and transport used for the maintenance of the micro gas turbine.
	Amount	1	1	1	1
	LocalName	Mikrogasturbine 100kWel	Erdgas, in Mikrogasturbine 100kWel	Biogas, in Mikrogasturbine 100kWel	Wartung Mikrogasturbine 100kWel
	Synonyms				
	GeneralComment	The module reflects a micro gas turbine system with 100 kW electrical output. Inventory based on information from literature and different manufacturers. Life time operation is 50'000 h.	The multioutput-process 'natural gas, burned in micro gas turbine delivers the coproducts 'heat, natural gas, allocation exergy, at micro gas turbine 100kWe' and 'electricity, natural gas, allocation exergy, at micro gas turbine 100kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The multioutput-process 'biogas, burned in micro gas turbine delivers the coproducts 'heat, biogas, allocation exergy, at micro gas turbine 100kWe' and 'electricity, biogas, allocation exergy, at micro gas turbine 100kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The module reflects a micro gas turbine system with 100 kW electrical output. Inventory is based on the maintenance costs of the micro gas turbine and estimations on the material use. Life time operation is 50'000 h with five maintenance operations during the life time.
	InfrastructureIncluded	1	1	1	1
	Category	natural gas	natural gas	biomass	natural gas
	SubCategory	cogeneration	cogeneration	cogeneration	cogeneration
	LocalCategory	Erdgas	Erdgas	Biomasse	Erdgas
	LocalSubCategory	Wärmekraftkopplung (WKK)	Wärmekraftkopplung	Wärmekraftkopplung	Wärmekraftkopplung
	Formula				
	StatisticalClassification				
	CASNumber				
TimePeriod	StartDate	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005
	DataValidForEntirePeriod	1	1	1	1
	OtherPeriodText				

Tab. 2.14 (Part 2) EcoSpold meta information for co-generation with a 100 kW$_{el}$ micro gas turbine

ReferenceFunction	Name	micro gas turbine 100kWe	natural gas, burned in micro gas turbine 100kWe	biogas, burned in micro gas turbine	maintenance micro gas turbine 100kWe
Geography	Location	CH	CH	CH	CH
ReferenceFunction	InfrastructureProcess	1	0	0	0
ReferenceFunction	Unit	unit	MJ	MJ	unit
Geography	Text	Process applicable in central European conditions.	Natural gas input modelled for Switzerland. Process applicable in central European conditions.	Biogas input modelled for conditions in Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.
Technology	Text	Radial turbine with recuperation for preheating the compressed air and fuel gas booster to increase gas pressure. Operation with connection to low pressure gas network. Electrical efficiency 29%, total efficiency 75%.	Radial turbine with recuperation for preheating the compressed air and fuel gas booster to increase gas pressure. Operation with connection to low pressure gas network. Electrical efficiency 29%, total efficiency 75%. Operation as base load engine with low partial load hours.	Radial turbine with recuperation for preheating the compressed air and fuel gas booster to increase gas pressure. Operation with refined biogas from low pressure gas network. Electrical efficiency 29%, total efficiency 75%. Operation as base load engine with low partial load hours.	Radial turbine with recuperation for preheating the compressed air and fuel gas booster to increase gas pressure. Operation with connection to low pressure gas network. Electrical efficiency 29%, total efficiency 75%.
Representativeness	Percent				
	ProductionVolume	unknown	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and estimations
	Extrapolations	none	none	none	none
	UncertaintyAdjustments	none	none	none	none
DataGeneratorAndPubl	Person	72	72	72	72
	DataPublishedIn	2	2	2	2
	ReferenceToPublishedSource	47	47	47	47
	Copyright	1	1	1	1
	AccessRestrictedTo	0	0	0	0
	CompanyCode				
	CountryCode				
	PageNumbers	Micro gas turbines	Micro gas turbines	Micro gas turbines	Micro gas turbines
ProofReading	Validator	42	42	42	42
	Details	automatic validation in Excel	automatic validation in	automatic validation in	automatic validation in
	OtherDetails	none	none	none	none

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3 SOFC fuel cell

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3.1 Introduction

Solid **O**xide **F**uel **C**ells (SOFC) use as electrolyte a solid, non-porous metal oxide ceramic (usually yttria-stabilized zirconia). As fuel for the cell, hydrogen or a mixture of H_2 and CO is used, which is derived from internal reforming of natural gas or other hydrocarbon fuels.

SOFC fuel cells for larger co-generation applications are already highly developed technologies. The main goal for further development is to reduce the high costs for the stack materials and the stack production. SOFC fuel cells are currently in operation as field test units in a power range from 1 kW_{el} up to 250 kW_{el}. Siemens Power Generation demonstrated with a 100 kW_{el} SOFC system continuous operation for over 20'000 hours and an electrical efficiency of 46 percent (Frey, 2005).

3.2 Characterisation of material product

Co-generation systems based on SOFC fuel cells have now reached the demonstration stage. Various units of up to 300 kW have been manufactured and tested in field tests. The vast majority of these systems are designed for operation with natural gas. The high operating temperature (typically 600 – 1000°C) make them suitable for larger co-generation applications with higher supply temperatures and also for applications where low pressure steam is needed. SOFC fuel cells have demonstrated the highest efficiencies for power generation systems, combined with minimal air emissions. Various manufacturers are currently developing SOFC fuel cell systems for central co-generation with a power range of above 100 kW_{el}, including Siemens Power Generation, Mitsubishi Heavy Industries, GE Energy, Rolls Royce and Ztek. Also smaller systems for residential co-generation units (< 10 kW_{el}) are under development by various manufacturers including Hexis, Acumentrics, Ceramic Fuel Cells andFuel Cell Technologies (Knight et al. 2005, Adamson 2006).

3.3 Use / application of product

SOFC fuel cell systems have excellent load-following characteristics but a long start up time due to the high operating temperature. This makes them suitable for co-generation applications where not many start ups occur (base load).

Operation with conventional fuels such as natural gas and propane are possible without a complicated reformation of the fuel as in PEM fuel cells needed. The high operating temperature of SOFC fuel cells makes them suitable for biogas or other liquid fuels such as kerosene or diesel. Only systems for co-generation applications operated with natural gas (or biogas in natural gas quality) are investigated.

3.4 System characterisation

Fig. 3.1 shows the system outline of the modelled SOFC fuel cell system. It is assumed that the turbine is connected to the Swiss and European low-pressure gas network (Faist Emmenegger et al. 2003). Natural gas (Faist Emmenegger et al. 2003) and biogas (Jungbluth et al. 2007) are included as energy carriers to operate the SOFC fuel cell system.

Natural gas (or biogas in natural gas quality) is the primary fuel of choice for residential co-generation applications. The operation of SOFC fuel cell system with low calorific gases such as landfill gas or digester gas is also possible if the desulphurisation system is adapted to the biogas composition. So far no field-tests with raw biogas are carried out. SOFC fuel cell systems operated with raw biogas drawn directly from the production site (e.g. an agricultural site or waste water plant) are not considered in this inventory.

A dataset of the heat production corresponding to each electricity dataset is also provided. Electricity production is given in kWh, heat production in MJ. It is assumed that the SOFC fuel cell system is operated in Switzerland (CH). However, the process is applicable also for central European conditions.

The infrastructure dataset refer to a 125 kWel SOFC fuel cell system with tubular cell design (Siemens 2006, Karakoussis et al. 2000). For future production of SOFC fuel cell systems an improved cell design and manufacturing process will be applied. This new production process is not considered in this inventory due to lack of data. The performance data for operation and the stack operating life are based on actual target values specified by the manufacturer. These values may not yet be reached but this is likely to happen within the next years. The emission levels used in the datasets are based on test data and target values specified by the manufacturer.

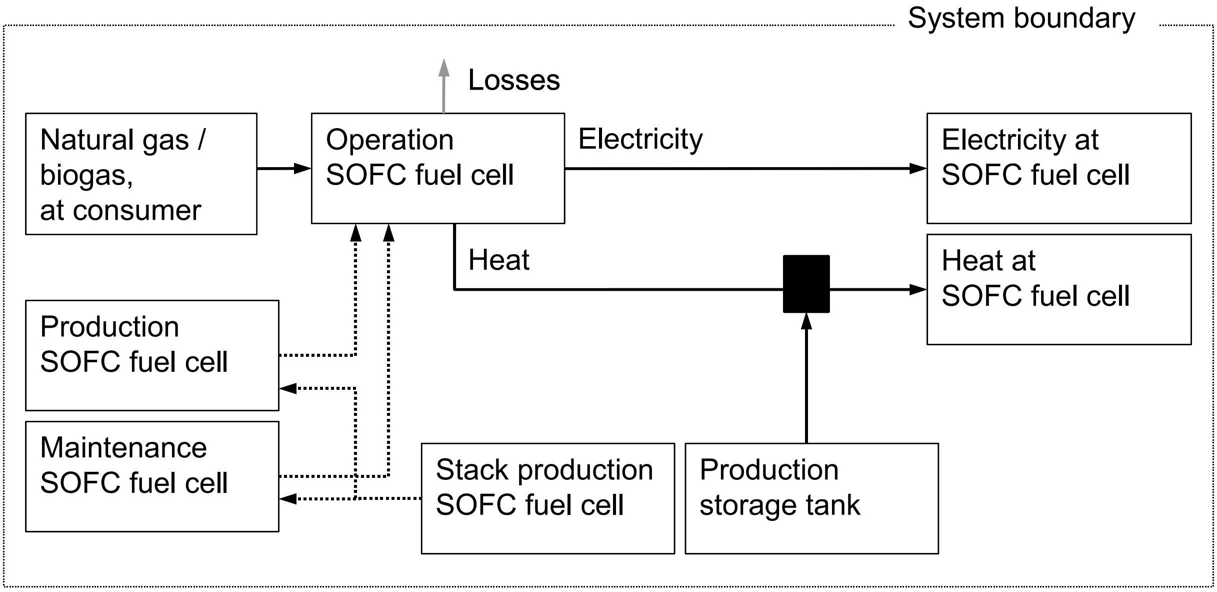

Fig. 3.1 **System outline of a 125 kW_{el} SOFC fuel cell system**

3.5 Natural gas, burned in SOFC fuel cell 125 kW_{el}

3.5.1 Technical Characteristics

SOFC fuel cells are available with an electrical output between 1 kW_{el} and 250 kW_{el}. A large unpressurised SOFC fuel cell system with 125 kW_{el} and 100 kW_{th} is analysed. Field test units of this size demonstrated an electrical efficiency of 46 percent and a total efficiency of 85 percent (Frey, 2005). The degradation of the stack performance (voltage) is as low as 0.1 percent per 1000 h of operation (Frey, 2005). For SOFC fuel cell systems with a power of > 100 kW_{el} the target values of electrical efficiencies (based on LHV) range between 44 and 56 percent and total efficiencies between 80 and 88 percent (Siemens 2006, DEA 2004, Krewitt et al. 2004).

SOFC fuel cells have a excellent partial-load operation efficiency. Similar to other fuel cell systems the cell stack efficiency improves at lower loads, resulting in an slight increase in the electrical efficiency of the system (Knight et al., 2005). The electrical efficiency remains constant down to 50 percent of the nominal load (Nadal, 1997).

An average electrical efficiency of 47 percent and a total efficiency of 80 percent are assumed for the operation of the 125 kW_{el} SOFC fuel cell system (see Tab. 3.1). The performance values used here are based on target values for serial products and are already reached in field tests.

Tab. 3.1 Electric and thermal efficiencies and losses for a 125kW_{el} SOFC fuel cell system

Electricity generation	MJ/MJ_{in}	0.47
Heat generation	MJ/MJ_{in}	0.33
Total energy output	MJ/MJ_{in}	0.80
Heat losses	MJ/MJ_{in}	0.20
Waste heat, total *)	MJ/MJ_{in}	0.631
*) Based on HHV; Natural gas, CH, high pressure: HHV 40.2 MJ/Nm^3; LHV = 36.5 MJ/Nm^3 and including losses as well as heat generated		

3.5.2 Equipment and maintenance needed

The infrastructure needed is defined by the total operating life and the maintenance intervals of the unit. The operating life of the unit is expected to reach 40'000 and 100'000 hours (Frey 2005, DEA 2005, Pehnt 2002). A operating life of 80'000 hours (full and partial load hours) with nine maintenance sessions during this period is assumed (maintenance every 8'000 hours). The maintenance of the fuel cell system (see Section 3.9) includes periodical catalyst and stack replacement. The operating life of the auxiliary systems is estimated as 15 years (Krewitt et al. 2004, Pehnt 2002).

For the operation of the SOFC fuel cell an average load factor similar to the operation of a 100 kW_{el} micro gas turbine is used. An average load factor of 81% is assumed. The fuel consumption is 266 kW at nominal load. Maintenance is needed every 6.89 TJ_{In} of fuel input, and the operating life of the unit is reached after 62.1 TJ_{In} of fuel input.

Besides the infrastructure of the SOFC fuel cell unit, which also includes the piping for the sanitary equipment, the electrical connections and the planning, a storage tank is needed to ensure good system performance. A storage volume of 8 m^3 is assumed. The inventory of the storage tank is based on the 10 m^3 storage tank described in Heck (2003). As in Heck (2003), the operating life of the storage tank is 100’000 hours or 77.6 TJ_{In} of fuel input.

A gas boiler for peak load and backup is used in order to reach a long operating period at full load. Depending on the variability of the heat requirement, this boiler is able to deliver up to 80% of the peak load. The gas boiler for peak load or backup is not included in this inventory because the system design depends strongly on the specific application.

The infrastructure processes included are summarised in Tab. 3.2.

Tab. 3.2 Equipment and maintenance of the SOFC fuel cell system operated with natural gas

Process	Operating life, interval	Amount
SOFC fuel cell 125kWe, future	80'000 h	1.61 E-8 units/MJin
Maintenance of SOFC fuel cell 125kWe, future	9 times per 80'000 h	1.45 E-7 units/MJin
Storage 10'000 l , *)	100'000 h	1.15 E-8 units/MJin
*) For 8 m^3 storage size 0.89 units are used.		

3.5.3 Energy and auxiliaries usage

Natural gas consumption

The technical characteristics described in Section 3.5.1 specify the use of natural gas from the Swiss low-pressure gas network. According to Faist Emmenegger et al. (2003), the gas has a lower heating value of 36.5 MJ/Nm^3 and a higher heating value of 40.2 MJ/Nm^3.

Water consumption

For each start up the SOFC fuel cell units needs 0.15 m^3 of filtered potable tap water (Siemens, 2006). During operation no additional water is needed. Because each start up of the unit takes up to 18 hours and reduces the stack lifetime, continuos operation must be achieved. Therefore only one start up every 8'000 hours for maintenance is assumed. The additional water consumption is therefore $2.4*10^{-5}$ kg/MJ_{In}.

3.5.4 Emissions to Air

Because SOFC fuel cell systems do not involve a combustion process like that of reciprocating engines, most of their air emissions are much lower. The major source of emissions is the fuel reforming process, because the heat that it requires is derived from the catalytic combustion of anode-off gas.

The CO_2 emissions for natural gas consumed from the Swiss gas network are 56 g/MJ_{In} (Faist Emmenegger et al. 2003).

Due to the low operating temperatures (below 1000°C), the emissions of nitrogen oxides are very low, at 0.9 to 5.8 mg/MJ_{In}.

The higher reaction temperatures in the SOFC fuel cell leads to low Carbon monoxide (CO) emissions. The reported carbon monoxide emissions range between 0 and 3.7 mg/MJ_{In}.

The behaviour of hydrocarbon emissions is similar to that of the carbon monoxide emissions. Under normal operating conditions, these emissions are very low (or undetectable). Most sources report only the total hydrocarbon emissions (THC). The reported emissions of unburnt hydrocarbons (excluding explicitly stated methane emissions) range between 0.3 and 1 mg/MJ_{In}. Hart and Bauen (1998) reported with 56 mg/MJ_{In} very high hydro carbon emissions. Probably this high value refers to an earlier system design. An average emission level of 0.7 mg/MJ_{In} NMVOC is used here.

Only two sources state separate methane emissions (Bazari 2004, Pehnt 2002). Compared to the total hydro carbon emissions reported in other sources these values is very high. An average emission level of 4 mg/MJ_{In} methane is used here.

The reported particulate emissions are zero. For this inventory particulate emissions are neglected.

The reported N_2O-emissions emissions are zero (Pehnt 2002, Krewitt et al. 2004). For this inventory N_2O-emissions are neglected.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. Because sulphur is toxic to the catalysts used here, it is removed by a catalytic reaction before entering the fuel processing unit. The SO_2 emissions therefore do not occur during operation but when the catalyst is regenerated. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied here.

The emission values used for operation with natural gas are summarised in Tab. 3.3.

Tab. 3.3 Emissions to air for SOFC fuel cell systems operated with natural gas

NOx mg/MJ_{In}	CO mg/MJ_{In}	THC mg/MJ_{In}	Particulates mg/MJ_{In}	SO_2 mg/MJ_{In}	Source
3.45	2.3	0.6	-	-	Knight et al. (2005)
< 2.8	-	-	-	< 0.03	Siemens (2006)
1	0	1	0	0	Krewitt et al. (2004)
1.87	3.74	9.36 *)	-	-	Bazari (2004), *)
2.8	2.3	0.6	-	-	Goldstein et al. (2003)
1	1.7	9.32 **)	0	0	Probas (2003) , **)
0.9	1.7	8.6 ***)	0	0	Pehnt (2002), ***)
<2	-	-	-	-	Jansen et al. (2000)
5.8	0.27	56 ****)	0	1.3	Hart and Bauen (1998), ****)
2.0	**1.7**	**4.7 *****)**	**0**	**0.55**	**Used in this inventory**

*) Additional 8.46 mg/MJ_{In} methane emission, in THC value included (0.9 mg/MJ_{In} NMVOC)
**) Additional 8.32 mg/MJ_{In} methane emission, in THC value included (1 mg/MJ_{In} NMVOC)
Emission values presented in Probas (2003) base partly on Pehnt (2002)
***) Additional 8.3 mg/MJ_{In} methane emission, in THC value included (0.3 mg/MJ_{In} NMVOC)
****) Very high hydro carbon and high NOx emissions might be explained with early design stage of system
*****) Thereof 4 mg/MJ_{In} as CH_4 and 0.7 mg/MJ_{In} as NMVOC

3.5.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future
- electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future

Further assessment of the environmental characteristics of fuel cells and competing technologies.

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is applied in this project. An allocation based on exergy leads to higher specific requirements and emissions per kWh of electricity compared to 1 kWh of heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 3.4.

Tab. 3.4 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	47 %	33 %	80 %
Exergy factor *)	1.000	0.170	-
Allocation factor	89.4 %	10.6 %	100.0 %

*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production

3.5.6 Data quality considerations

Tab. 3.5 shows the multi-output process raw data and data-quality indicators of the inventory of natural gas, burned in SOFC fuel cell 125kWe, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far not available as serial product, the performance data are based on field test results and target values which are expected to be reached in about 5 years with a serial product.

Tab. 3.5 Multi-output process raw data of natural gas, burned in SOFC fuel cell 125 kW$_{el}$, future

	Name	Location	InfrastructureProcess	Unit	natural gas, burned in SOFC fuel cell 125kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	CH	0	MJ	3.30E-1				100	0
	electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	CH	0	kWh	1.31E-1				0	100
technosphere	SOFC fuel cell 125kWe, future	CH	1	unit	1.61E-8	1	1.14	(2,3,2,1,1,4); uncertainty of life time	10.6	89.4
	maintenance SOFC fuel cell 125kWe, future	CH	0	unit	1.45E-7	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	10.6	89.4
	storage 10'000 l	RER	1	unit	1.15E-8	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	natural gas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	10.6	89.4
	tap water, at user	CH	0	kg	2.40E-5	1	1.26	(3,4,2,2,1,5); company data	10.6	89.4
emission air, high population density	Carbon dioxide, fossil	-	-	kg	5.60E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	10.6	89.4
	Carbon monoxide, fossil	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on different references	10.6	89.4
	Methane, fossil	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on few references	10.6	89.4
	Nitrogen oxides	-	-	kg	2.00E-6	1	1.53	(2,3,2,1,1,4); estimate based on different references	10.6	89.4
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	7.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on different references	10.6	89.4
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	10.6	89.4
	Heat, waste	-	-	MJ	6.31E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	10.6	89.4

3.6 Biogas gas, burned in SOFC fuel cell 125 kW$_{el}$

3.6.1 Technical Characteristics

The operation of SOFC fuel cells with low calorific gases such as landfill gas or digester gas is also possible when the desulphurisation system is adapted to the biogas composition. So far no field-test results of large SOFC fuel cells operated with biogas are available. Therefore SOFC fuel cell systems operated with raw biogas directly from the production site (e.g. agricultural site or waste water plant) are not considered.

Only biogas distributed in the regular natural gas network is considered. This biogas has a quality similar to natural gas. Its methane content must be at least 96 vol-%.

Under these conditions the operation of the SOFC fuel cell with biogas is similar to the operation with natural gas (see Section 3.5.1). For operation of the SOFC fuel cell with refined biogas an average electrical efficiency of 47 percent and a total efficiency of 80 percent is assumed (see Tab. 3.6).

Tab. 3.6 Electric and thermal efficiencies and losses for a 125kW$_{el}$ SOFC fuel cell system

Electricity generation	MJ/MJ$_{in}$	0.47
Heat generation	MJ/MJ$_{in}$	0.33
Total energy output	MJ/MJ$_{in}$	0.80
Heat losses	MJ/MJ$_{in}$	0.20
Waste heat, total *)	MJ/MJ$_{in}$	0.637
*) Based on HHV; Biogas, CH, high pressure: HHV 38.146 MJ/Nm^3; LHV = 34.450 MJ/Nm^3 and including losses as well as heat generated		

3.6.2 Equipment and maintenance needed

The infrastructure needed is identical to that of an engine operated with natural gas presented in Section 3.5.2 (Tab. 3.2). An operating life of 80'000 hours with nine maintenance sessions during the operating life is assumed. Maintenance is needed every 6.89 TJ$_{In}$ of fuel input and the operating life of the unit is reached after 62.1 TJ$_{In}$ of fuel input. As for the unit operated with natural gas, a storage tank volume of 8 m^3 is assumed, which has to be replaced after every 77.6 TJ$_{In}$ of fuel input. An average load factor of 81% is assumed as defined for operation with natural gas.

3.6.3 Energy and auxiliaries usage

Biogas consumption

The distribution requirements (energy, leakages) are similar to those of natural gas. Only the composition of the emissions differs due to the different compositions of biogas and natural gas. The dataset “methane, 96 vol-%, from biogas, low pressure, at consumer” is used as the process input for the SOFC fuel cell. According to Jungbluth et al. (2007), the gas has a lower heating value of 34.45 MJ/Nm^3 and a higher heating value of 38.15 MJ/Nm^3. On the basis of the lower heating value, 0.029 Nm^3/MJ$_{In}$ of biogas are required.

Water consumption

As for the operation with natural gas an additional water consumption of $2.4*10^{-5}$ kg/MJ$_{In}$ is included.

3.6.4 Emissions to Air

The biogenic CO_2 emissions are calculated on the basis of the carbon content of the biogas mix. The values presented in Tab. 3.7 also take into account carbon emitted in the form of CO, CH_4 and NMVOC. For operation of the SOFC fuel cell system with refined biogas, identical emission factors are used to those for operation with natural gas (see Section 3.5.4).

According to the biogas composition presented in Jungbluth et al. (2007), the refined biogas has a slightly lower nitrogen content than natural gas. Due to the low NO_X emissions of SOFC fuel cells, this difference is neglected and identical emission factors are used. An NO_X emission factor of 2 mg NO_X/MJ_{In} is applied.

The higher reaction temperatures in the SOFC fuel cell leads to low Carbon monoxide (CO) emissions. As for operation with natural gas an emission factor of 1.7 mg CO/MJ_{In} is applied here.

Under normal operating conditions, these emissions are very low (or undetectable). Most sources report only the total hydrocarbon emissions (THC). The reported emissions of unburnt hydrocarbons (excluding explicitly stated methane emissions) range between 0.3 and 1 mg/MJ_{In}. Hart and Bauen (1998) reported with 56 mg/MJ_{In} very high hydro carbon emissions. Probably this high value refers to an earlier system design. An average emission level of 0.7 mg/MJ_{In} NMVOC is used here.

Only two sources state separate methane emissions (Bazari 2004, Pehnt 2002). Compared to the total hydro carbon emissions reported in other sources these values is very high. An average emission level of 4 mg/MJ_{In} methane is used here.

The reported particulate emissions are zero. For this inventory particulate emissions are neglected.

The reported N_2O-emissions emissions are zero (Pehnt 2002, Krewitt et al. 2004). For this inventory N_2O-emissions are neglected.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. The H_2S content in odorated natural gas is similar to that of the biogas presented in Jungbluth (2007). Because sulphur is toxic to the catalysts used, it is removed by a catalytic reaction before entering the fuel processing unit. The SO_2 emissions therefore do not occur during operation but when the catalyst is regenerated. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied here.

Tab. 3.7 CO_2-emissions and carbon balance

	Emission factor	Carbon content	Share
Biogas input	-	524'992.3 mg C / Nm^3 15'239.3 mg C / MJ_{In}	100.00 %
Carbon dioxide, biogenic	55'823.0 mg/MJ_{In}	15'235.0 mg C / MJ_{In}	99.97 %
Carbon monoxide, biogenic	1.7 mg/MJ_{In}	0.7 mg C / MJ_{In}	0.01 %
Methane, biogenic	4 mg/MJ_{In}	3.0 mg C / MJ_{In}	0.02 %
NMVOC *)	0.7 mg/MJ_{In}	0.6 mg C / MJ_{In}	0.00 %
*) Carbon content calculated as C5H12 (Pentane)			

3.6.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, biogas, allocation exergy, at SOFC fuel cell 125kWe, future
- electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is used in this project. Allocations based on exergy lead to higher specific requirements and emissions per kWh of electricity compared to 1 kWh heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in In Tab. 3.8 .

Tab. 3.8 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	47 %	33 %	80 %
Exergy factor *)	1.000	0.170	-
Allocation factor	89.4 %	10.6 %	100.0 %
*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production			

3.6.6 Data quality considerations

Tab. 3.9 shows the multi-output process raw data raw data and data-quality indicators of the inventory of biogas, burned in SOFC fuel cell 125kWe, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far not available as serial product, the performance data are based on field test results and target values which are expected to be reached in about 5 years with a serial product.

Tab. 3.9 Multi-output process raw data of biogas, burned in SOFC fuel cell 125 $\mathrm{kW_{el}}$, future

	Name	Location	InfrastructureProcess	Unit	biogas, burned in SOFC fuel cell 125kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	CH	0	MJ	3.30E-1				100	0
	electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	CH	0	kWh	1.31E-1				0	100
technosphere	SOFC fuel cell 125kWe, future	CH	1	unit	1.61E-8	1	1.14	(2,3,2,1,1,4); uncertainty of life time	10.6	89.4
	maintenance SOFC fuel cell 125kWe, future	CH	0	unit	1.45E-7	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	10.6	89.4
	storage 10'000 l	RER	1	unit	1.15E-8	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	10.6	89.4
	tap water, at user	CH	0	kg	2.40E-5	1	1.26	(3,4,2,2,1,5); company data	10.6	89.4
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	5.58E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of biogas	10.6	89.4
	Carbon monoxide, biogenic	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on different references	10.6	89.4
	Methane, biogenic	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on few references	10.6	89.4
	Nitrogen oxides	-	-	kg	2.00E-6	1	1.53	(2,3,2,1,1,4); estimate based on different references	10.6	89.4
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	7.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on different references	10.6	89.4
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	10.6	89.4
	Heat, waste	-	-	MJ	6.37E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	10.6	89.4

3.7 Manufacture of a SOFC fuel cell 125kW$_{el}$

3.7.1 Technical Characteristics

The infrastructure dataset of the 125 kW$_{el}$ SOFC fuel cell unit includes the most important materials used for its production, the transport of these materials and the energy needed for production and engineering. The production process involves different steps from raw material cutting, casting, machining and welding. Steel but also stainless steel (reformer unit), high temperature alloys (Ni-Alloy), ceramics and catalyst materials (nickel, zinc) are used. The total weight of a 125 kW$_{el}$ SOFC fuel cell unit vary largely between the different sources. The specific weight ranges from 40 to 200 kg per kW$_{el}$ (Fuel Cells 2005, Siemens 2006). The specific weight of 128 kg per kW$_{el}$ of a similar 250 kW$_{el}$ prove of concept design is used for the inventory of the materials. This leads to a total plant weight of 16’000 kg for the 125 kW$_{el}$ SOFC fuel cell unit.

3.7.2 Infrastructure

No data are available on the production infrastructure for SOFC fuel cell units. The infrastructure size is approximated with a production facility for similar products (Viessmann 2005). This production site includes 35,300 m^2 of floor space (offices, production and storage). An output of 630 units per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17,700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105,900 m^3. The service life of the buildings is assumed to be 50 years. Each unit bears the environmental burdens of 0.56 m^2 of the building hall and 3.4 m^3 of the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with the data of a similar production site (Viessmann 2005). On this site, 63,500 m^2 is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of 2.02 m^2 of land transformation and 101 m^2 a of land occupation.

3.7.3 Raw materials, energy and auxiliaries

The amount of raw materials to produce the 125 kW$_{el}$ SOFC fuel cell unit is derived from Karakoussis et al. (2000). In these data the material and the production energy for the SOFC fuels cell unit are included. The energy demand for the heating of the production halls, machining steel parts and transport requirements are not included. The specific weight of the materials included in Karakoussis et al. (2000) is 72 kg per kW$_{el}$. Material (mainly steel or stainless steel) used for the steel-frame, auxiliary systems and sanitary installations are not included in this data and had to be added.

The data presented in Karakoussis et al. (2000) for the inverse rectifier show a too small total material weight (0.33 kg/kW) for a 125 kW$_{el}$ inverter. According to Solarmarkt (2006) the specific weight of a 125 kW$_{el}$ inverse rectifier ranges between 4 and 9 kg/kW. The inverse rectifier described in Jungbluth & Tuchschmid (2007) is used. Due to the smaller size (2.5 kW$_{el}$) of this unit, an amount of 50 units is used for this inventory.

Additional steel (frame; covers) and stainless steel (auxiliary systems) materials are included in order to reach the correct plant weight. Not all material for piping, heat exchanger, fram and cover are included in the data of Karakoussis et al. (2000). According to the balance of plant presented for a 100 kW$_{el}$ SOFC fuel cell unit in Pehnt (2002) additional 1’800 kg stainless steel are expected to be used for the 125 kW$_{el}$ unit. Further 4’370 kg carbon steel and 1’800 kg stainless steel are additionally included in order to reach the correct plant weight (see Tab. 3.10).

An additional energy requirement of 61.1 GJ for heat (natural gas, at industrial furnace >100 kW) and 3.26 MWh of electricity (medium voltage, production UCTE, at grid) is included for heating and electricity on the production site. The amount used is based on the specific energy requirement per kg product of a similar production site (Viessmann 2005). For the other materials the electricity used for the production process (22.2 kWh/kWel) is taken from Karakoussis et al. (2000).

No data are available for the water consumption for the manufacturing of the SOFC fuel cell unit. The amount used (see Tab. 3.10) bases on the specific water demand of 1.22 litre per kg product of a similar production site (Viessmann 2005).

For the transportation of the raw materials, the standard distances for Europe according to (Frischknecht et al., 2004) are applied. For metals and plastics, 200 km for rail transport and 100 km for road transport (lorry >16t, fleet average) are used here. These distances are also applied to the fuel cell stack because it is not manufactured at the same location as the total unit. For the installation of the unit, a distance of 200 km by road transport is assumed (lorry >16t, fleet average).

Additional material and energy is needed for auxiliary installations outside of the fuel cell unit itself (e.g. sanitary ducting). These parts are modelled with the dataset “heating, sanitary equipment cogen unit 160kWe” described in Heck (2003). In view of the larger size of the CHP unit described in Heck (2003), only 75% of this amount is used.

The material and energy required for the foundations is modelled according to the dataset of the 10 m^2 foundations described in Heck (2003). According to the dimension presented in Siemens (2006) for the 125 kW_{el} SOFC fuel cell system a foundation of 35 m^2 is needed.

Additional energy is consumed for planning and engineering. Due to the similar size as compared to the micro gas turbine also similar expenditures for engineering are assumed. Because the integration of a large fuel cell unit is not a standard “everyday business”, 50% higher expenditures for planning and engineering than for a 100 kW_{el} micro gas turbine system is assumed. For the 125 kW_{el} unit 600 working hours of planning and engineering are assumed. On the basis of data from Aebischer and Catenazzi (2006), a specific energy consumption of 15 MJ/h of heat (light fuel oil, burned in a 100-kW boiler, non-modulating) and 2 kWh/h of electricity (low voltage, at grid, CH) is used to calculate the energy requirement. It is assumed that the construction site is visited 15 times and the distance of 200 km (return trip) for each visit is covered by car.

The material and energy data presented in Karakoussis et al. (2000) bases on a 100 kW_{el} tubular SOFC fuel cell system. These data are scaled up (linearly) to a 125 kW_{el} system. The data used in the inventory are shown in Tab. 3.10.

Tab. 3.10 Raw materials, energy and auxiliaries of the manufacture of a 125kW$_{el}$ SOFC fuel cell system

Size of the SOFC fuel cell unit (nominal electrical power)	Unit -	Karakoussis et al. (2000) 100 kW$_{el}$	Used in this study 125 kW$_{el}$	Remarks	
Reinforcing steel, at plant	kg	5900	11750	1)	R
Chromium steel 18/8, at plant	kg	0	1800	1)	R
Aluminium oxide, at plant	kg	420	525		L
Alumina-silica insulation material	kg	50	63	2)	L
Iron-nickel-chromium alloy, at plant	kg	200	250		R
Nickel, 99.5%, at plant	kg	20	25		R
Zinc catalyst for desulphuriser	kg	1	1.25	3)	R
Sheet rolling, steel	kg	Not available	11750	4)	
Sheet rolling, chromium steel	kg	Not available	2050	4)	
Transport, freight, rail, RER	tkm	Not available	3200	5)	
Transport, lorry >16t, fleet average, RER	tkm	Not available	1600	5)	
Engine installation: transport, lorry >28t, fleet av., CH (200 km)	tkm	Not available	3200		
Stack SOFC fuel cell 125kWe, future	unit	s. Chapt., 3.8	1		
Inverter, 2500W, at plant (2.5 kWel)	unit	data not used	50	6)	
Heating, sanitary equipment cogen unit 160kWe	unit	Not available	0.75		
Construction work, cogen unit 160kWe (10 m^2 foundation)	unit	Not available	3.5	7)	
Water for manufacturing (unspecified natural origin)	m3	Not available	19.52	8)	W
Heating production site: natural gas, at industrial furnace >100kW	GJ	Not available	61.1	8)	
Electricity production site: medium voltage, production UCTE, at grid	MWh	2.22	6.04	9)	
Heating engineering services: light fuel oil, burned in boiler 100kW, non-modulating	GJ	Not available	9		
Electricity engineering services: low voltage, at grid, at grid, CH	MWh	Not available	1.2		
Transport engineering: transport, passenger car, CH	pkm	Not available	3000		
Dismantling: R = Recycling; L = Landfilled; W = Disposal in wastewater plant 1) Additional material included due to higher total plant weight according to (Fuel Cells 2005, Siemens 2006) 2) Proxy process "aluminium oxide, at plant" used in this inventory 3) Proxy process "zinc for coating, at regional storage" used in this inventory 4) For pre-fabrication of raw materials used 5) Standard distances for Europe (200 km rail, 100 km road) also used for stack and inverse rectifier 6) Ecoinvent process for inverse rectifier used instead of the data presented in Karakoussis et al. (2000) 7) Factor determined on the basis of the required surface 8) Approximation with data from Viessmann (2005) 9) Electricity demand for manufacturing of additional material approximated with data from Viessmann (2005)					Dismantling

3.7.4 Emissions to air and water

Emissions to air are included in the processes unit used (e.g. heating or transport processes). No further process-related air emissions occur. An average wastewater treatment process is used for the wastewater disposal due to a lack of data on water emissions from manufacturing. It is assumed that all the fresh water used is disposed of as wastewater via a suitable treatment plant.

3.7.5 Dismantling

After their service life SOFC fuel cells will be dismantled and the materials recycled or disposed of. It is assumed that all metals and catalyst material (zinc, nickel) will be recycled No environmental burdens from dismantling and recycling are included for these materials (cut-off). Final disposal of the ceramic materials in a inert material landfill is assumed. The amount and type of disposal of the different materials is indicated in Tab. 3.10. Depending on the waste treatment process additional water content of the waste is added to the weight of the disposed material (e.g. for inert material). The values used in Tab. 3.11 includes the water content of the waste.

3.7.6 Data quality considerations

Tab. 3.11 shows the unit process raw data and data-quality indicators of the manufacture of a SOFC fuel cell unit with 125 kW_{el} electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for different additional processes not covered in the data source. Large uncertainties exist for total amount of steel material, because the values given for the total weight of a serial product differ largely between the manufacturers. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 3.11 Unit process raw data of the manufacture of a 125kW$_{el}$ SOFC fuel cell system

	Name	Location	InfrastructureProce	Unit	SOFC fuel cell 125kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	SOFC fuel cell 125kWe, future	CH	1	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	1.18E+4	1	1.46	(4,5,3,2,3,5); data for future 125kWel plant design, value uncertain
	chromium steel 18/8, at plant	RER	0	kg	1.80E+3	1	1.46	(4,5,3,2,3,5); data for future 125kWel plant design, value uncertain
	iron-nickel-chromium alloy, at plant	RER	0	kg	2.50E+2	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	aluminium oxide, at plant	RER	0	kg	5.88E+2	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	nickel, 99.5%, at plant	GLO	0	kg	2.50E+1	1	1.60	(2,4,3,2,4,5); data from 100kWel plant design adapted
	zinc, primary, at regional storage	RER	0	kg	1.25E+0	1	1.60	(2,4,3,2,4,5); data from 100kWel plant design adapted
	stack SOFC fuel cell 125kWe, future	CH	1	unit	1.00E+0	1	3.00	(nA.,nA.,nA.,nA.,1,nA.); material
	inverter, 2500W, at plant	RER	1	unit	5.00E+1	1	3.33	(4,4,2,2,4,5); data from 3kWel unit for use in photovoltaics
	heating, sanitary equipment cogen unit 160kWe	RER	1	unit	7.50E-1	1	3.16	(4,4,2,5,3,5); approximation based on similar process
	construction work, cogen unit 160kWe	RER	1	unit	3.50E+0	1	3.12	(2,4,3,2,3,5); data from 160 kWel engine cogen plant adapted
	sheet rolling, steel	RER	0	kg	1.18E+4	1	1.25	(2,4,2,2,1,5); based on material input
	sheet rolling, chromium steel	RER	0	kg	2.05E+3	1	1.25	(2,4,2,2,1,5); based on material input
	transport, freight, rail	RER	0	tkm	3.20E+3	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	1.60E+3	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >28t, fleet average	CH	0	tkm	3.20E+3	1	2.16	(4,4,2,1,3,5); estimation for transport of fuel cell to site
	transport, passenger car	CH	0	pkm	3.00E+3	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	6.11E+4	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	9.00E+3	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	6.04E+3	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	electricity, low voltage, at grid	CH	0	kWh	1.20E+3	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	6.17E+2	1	1.35	(2,4,3,2,3,5); approximation for disposal of ceramic parts
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.95E+1	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	3.40E+0	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
	building, hall, steel construction	CH	1	m2	5.60E-1	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
resource, in water	Water, unspecified natural origin	-	-	m3	1.95E+1	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	1.01E+2	1	1.65	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, from unknown	-	-	m2	2.02E+0	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, to industrial area, built up	-	-	m2	2.02E+0	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
emission air, high population density	Heat, waste	-	-	MJ	2.61E+4	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

3.8 Manufacture of Stack SOFC fuel cell 125kW$_{el}$

3.8.1 Technical Characteristics

The infrastructure dataset of the 125 kW$_{el}$ SOFC fuel cell stack includes the most important materials used for its production, the transport of these materials and the energy needed for its production. The production process involves various steps including raw material preparation (oxide mixing), extrusion, plasma spraying, electrochemical vapor deposition (EVD), drying and sintering. Metal oxides, nickel and various chemicals (e.g. binder and solvent) are the materials used. The total weight of the analysed stack is 700 kg.

3.8.2 Infrastructure

No data are available on the infrastructure for SOFC fuel-cell stack production. The infrastructure size is approximated with a production facility for conventional heating systems (Viessmann 2005). This production site includes 35,300 m^2 of floor space (offices, production and storage). An output of 14'500 stacks per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17,700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105,900 m^3. The service life of the buildings is assumed to be 50 years. Each unit bears the environmental burdens of 24.4*10^{-3} m^2 for the building hall and 0.146 m^3 m^3 for the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with the data of a similar production site (Viessmann 2005). On this site, 63,500 m^2 is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of 87.6*10^{-3} m^2 land transformation and 4.38 m^2 a of land occupation.

3.8.3 Raw materials, energy and auxiliaries

The amount of raw materials used for the production of the 125 kW$_{el}$ SOFC fuel cell stack is derived from Karakoussis et al. (2000). The material for the stack and the electricity needed for production is included in this data. Not included is the energy demand for the heating of the production halls, the preparation of the oxide powders and the transport requirements.

Oxide powder preparation

To obtain the desired oxide powder mixture the pure oxides are dissolved in nitric acid, mixed and then spray dried and dried at 900°C (Zapp, 1998). The amount of nitric acid needed is calculated using the process description given in Zapp (1998). The required energy for the dying process is according to Zapp (1998) 772 MJ per kg powder product. This value bases on a laboratory scale spray drier and oven. For mass production of ceramic tiles spray drying and drying processes use only 1.3 to 3.6 MJ per kg of product (IPPC, 2006). The heat demand for the drying process requires at least 2.7 MJ per kg of product calculating with the amount of water evaporating (or 2.3 MJ per kg evaporated water). A spray drying process as used in the chemical industry typically requires about 45 MJ per kg evaporated water. This leads to an energy demand of 55 MJ per kg of product. This value is used as average value. For the material of the whole stack an energy demand of 29.7 GJ is required. It is assumed that this heat is generated with a natural gas industrial furnace.

It is assumed that a selective catalyst reduction unit (SCR) is used to reduce NOx emissions in the flue gas. For the operation of this unit 350 kg urea is needed. The amount is calculated based on the values given in Heck (2003).

For the electrochemical vapor deposition of the electrode the zirconium dioxide has to be treated with chlorine to obtain zirconium chloride ($ZrCl_4$). For this process 85 kg chlorine and 14 kg petroleum coke is needed.

Within the last years the cell design has been improved and some energy intensive processes were replaced[1]. This changes within the production process are not considered in this inventory, because from the new production process no data are available. A different process presented in Pehnt (2002) for a future SOFC fuel cell stack production process for a unit with 100 kW_{el} (planar cell design) shows a even higher electricity demand. The electricity demand as presented in Karakoussis et al. (2000) is used for this inventory.

An additional energy requirement of 2.67 GJ for heating (natural gas, at industrial furnace >100kW) is included for each stack (125 kWel). This amount is based on the specific energy requirement of 3.8 MJ per kg of product for a similar production site (Viessmann 2005).

For the transportation of the raw materials, except of the metal oxides, the standard distances for Europe according to (Frischknecht et al., 2004) are applied. For lanthanum oxide, which is imported from China 24'000 km freight ship-, 1'200 km rail- and 200 km road-transport (lorry >16t, fleet average) are applied. For zirconium dioxide which is imported from Australia 20'000 km freight ship-, 800 km rail- and 200 km road-transport (lorry >16t, fleet average) are applied.

The material and energy data presented in Karakoussis et al. (2000) bases on a 100 kW_{el} tubular SOFC fuel cell system. These data are scaled up (linearly) to a 125 kW_{el} system. The data used for the inventory are shown in Tab. 3.12.

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[1] In new designs Electrochemical Vapour Deposition (EVD) process is replaced with Atmospheric- plasma spray (APS)

Tab. 3.12 Raw materials, energy and auxiliaries of the manufacture of a 125kW$_{el}$ SOFC fuel cell stack

Size of the SOFC fuel cell unit (nominal electrical power)	**Unit -**	**Used in this study 125 kW$_{el}$**	**Remarks**	
LaMnO3 powder	kg	532	1)	L
LaCrO3 powder	kg	7.75	2)	L
Zirconium chloride powder	kg	104	3)	L
Yttrium chloride powder	kg	15.3	3)	L
Zirconium oxide powder	kg	9.75		L
Nickel Oxide	kg	9.75	4)	R
Nickel	kg	0.0125		R
Ethanol	kg	23.4		(E)
Polyvinylbutyral (PVB)	kg	3.88	5)	(E)
Polyethyleneglycol	kg	1.5	6)	(E)
Dibutylphthalat	kg	1.5	7)	(E)
Water, deionised	kg	123		-
Nitric acid, for powder preparation	kg	712	8)	(E)
Chlorine, for carbochlorination of oxide powder	kg	85	9)	(E)
Petroleum coke, for carbochlorination of oxide powder	kg	14	9)	
Urea, as N, for SCR emission treatment	kg	350	10)	
Transport, freight, rail, RER	tkm	1690	11)	
Transport, lorry >16t, fleet average, RER	tkm	300	11)	
Transport, transoceanic freight ship	tkm	10700	11)	
Heating production site: natural gas, at industrial furnace >100kW	GJ	2.67	12)	
Spray drying process: natural gas, at industrial furnace >100kW	GJ	29.7	13)	
Electricity, medium voltage, production UCTE, at grid	MWh	9.54		
Dismantling: R = Recycling; L = Landfilled; (E) = Partly emitted to air or water 1) Accounted as 368 kg lanthanum oxide and 127 kg manganese 2) Accounted as 5.25 kg lanthanum oxide and 1.3 kg chromium 3) Accounted together with yttrium chloride powder as 75 kg zirconium dioxide 4) Accounted as 7.67 kg nickel , 99.5% 5) Accounted as 5.23 kg vinyl acetate 6) Accounted as 1.67 kg diethyleneglykol 7) Accounted as 0.9 kg butanol and 0.9 kg phthalic anhydride 8) Amount for dissolving metal oxides for powder preparation with spray dry process according to Zapp (1998) 9) Auxiliary material for carbochlorination of oxide powder for electrochemical vapour deposition of electrode 10) Auxiliary material for SCR emission reduction for spray dry process 11) Standard distances for Europe used for raw materials, additional transport distances for oxide powders 12) Approximation with data from Viessmann (2005) 13) Estimated energy demand for powder spray dry process: 55 MJ per kg of powder product				Dismantling

3.8.4 Emissions to Air and Water

Most emissions to air are included in the unit processes used (e.g. heating or transport processes). The air emissions from the solvent used (propanol) in the production process are included. It is assumed that 100% of the used solvent (0.019 kg) is emitted to air.

Most emissions to air are included in the unit processes used (e.g. heating or transport processes). Additional emissions occur from the spray drying process, where the nitrogen of the nitric acid is emitted. It is assumed that a selective catalyst reduction unit (SCR) is installed. According to CSM (2006) typically 90 to 97 percent NOx reduction is achieved. It is assumed that NOx emissions in the flue gas are reduced to 5% of the stoechiometric amount. This leads to 26 kg NOx emissions from the spray drying process and 4 kg NH_3 emissions due to ammonia slip from the SCR unit.

During stack production emission from the use of solvents and binder occurd during thermal processes. According to the future production process described in Pehnt (2002) about 30% of the solvent input is emitted as NMVOC. This leads to the following emissions to air per stack: 7 kg ethanol, 0.45 kg diethyleneglykol and 1.6 kg NMVOC.

Chloride ions from the chlorinated metal oxides are considered as emissions to water. It is assumed that the chlorine is scrubbed from the flue gas of the EVD process and is emitted to the waste water. An amount of 85 kg chloride emissions to water per stack are applied.

3.8.5 Dismantling

After their service life, the SOFC fuel cell stacks will be dismantled and the materials recycled or disposed of. There are no data available about which materials will be reused or not. It is assumed that the nickel in the stack will be recycled. No environmental burdens from dismantling and recycling are included (cut-off) for these materials. For the ceramic stack materials a recycling is probably not possible. For 702 kg (669 kg + 5% water) a final disposal as inert material on a landfill is assumed. The amount and type of disposal of the different stack materials is indicated in Tab. 3.12. The values used in Tab. 3.13 includes the water content of the waste.

3.8.6 Data quality considerations

Tab. 3.13 shows the unit process raw data and data-quality indicators of the manufacture of a SOFC fuel cell stack with 125 kW_{el} electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for various additional processes not covered in the data source. Some data of the material and processes used are uncertain due to the fast development of the technology. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 3.13 Unit process raw data of the manufacture of a 125kW$_{el}$ SOFC fuel cell stack

	Name	Location	InfrastructureProce	Unit	stack SOFC fuel cell 125kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	stack SOFC fuel cell 125kWe, future	CH	1	unit	1			
technosphere	lanthanum oxide, at plant	CN	0	kg	3.73E+2	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	zirconium oxide, at plant	AU	0	kg	8.48E+1	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	manganese, at regional storage	RER	0	kg	1.27E+2	1	1.61	(3,4,3,2,4,5); proxy for mangan oxide, data from 100kWel plant design adapted
	chromium, at regional storage	RER	0	kg	1.30E+0	1	1.61	(3,4,3,2,4,5); proxy for chromium oxide, data from 100kWel plant design adapted
	nickel, 99.5%, at plant	GLO	0	kg	7.68E+0	1	1.61	(3,4,3,2,4,5); proxy for nickel oxide, data from 100kWel plant design adapted
	ethanol from ethylene, at plant	RER	0	kg	2.34E+1	1	1.36	(3,4,3,2,3,5); data from 100kWel plant design adapted
	vinyl acetate, at plant	RER	0	kg	5.23E+0	1	2.12	(4,4,3,2,5,5); proxy for PVB, data from 100kWel plant design adapted
	diethylene glycol, at plant	RER	0	kg	1.58E+0	1	2.12	(4,4,3,2,5,5); proxy for polyethylene-glycol, data from 100kWel plant design
	butanol, 1-, at plant	RER	0	kg	9.00E-1	1	2.12	(4,4,3,2,5,5); proxy for dibutylpthalat, data from 100kWel plant design
	phthalic anhydride, at plant	RER	0	kg	9.00E-1	1	2.12	(4,4,3,2,5,5); proxy for dibutylpthalat, data from 100kWel plant design
	petroleum coke, at refinery	RER	0	kg	1.40E+1	1	2.12	(4,4,3,2,5,5); estimation for process of powder carbochlorination
	chlorine, liquid, production mix, at plant	RER	0	kg	8.50E+1	1	2.12	(4,4,3,2,5,5); estimation for process of powder carbochlorination
	nitric acid, 50% in H2O, at plant	RER	0	kg	7.12E+2	1	1.61	(3,4,3,2,4,5); estimation for process of powder mixing
	urea, as N, at regional storehouse	RER	0	kg	3.50E+2	1	1.41	(4,4,3,2,3,5); estimation for SCR in spray drier for NOx reduction
	water, deionised, at plant	CH	0	kg	1.23E+2	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	transport, freight, rail	RER	0	tkm	1.69E+3	1	2.09	(4,5,nA,nA,nA,nA); mainly standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	3.00E+2	1	2.09	(4,5,nA,nA,nA,nA); mainly standard distances used
	transport, transoceanic freight ship	OCE	0	tkm	1.07E+4	1	2.16	(4,4,2,1,3,5); estimation according to origin of powder raw material
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	3.24E+4	1	2.12	(4,4,3,2,5,5); estimation for process of powder mixing
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	9.54E+3	1	1.35	(2,4,3,2,3,5); data from 100kWel plant design adapted
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	7.02E+2	1	1.64	(4,4,2,2,4,5); approximation for disposal of ceramic parts
	building, multi-storey	RER	1	m3	1.46E-1	1	3.34	(4,4,2,5,4,5); rough estimation based on company data of similar branch
	building, hall, steel construction	CH	1	m2	2.44E-2	1	3.34	(4,4,2,5,4,5); rough estimation based on company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	4.38E+0	1	1.90	(4,4,2,5,4,5); rough estimation based on company data of similar branch
	Transformation, from unknown	-	-	m2	8.76E-2	1	2.35	(4,4,2,5,4,5); rough estimation based on company data of similar branch
	Transformation, to industrial area, built up	-	-	m2	8.76E-2	1	2.35	(4,4,2,5,4,5); rough estimation based on company data of similar branch
emission air, high population density	Ethanol	-	-	kg	7.00E+0	1	1.69	(4,4,2,2,3,5); rough estimation based on material input
	Diethylene glycol	-	-	kg	4.50E-1	1	2.35	(4,4,3,2,5,5); rough estimation based on material input
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	1.60E+0	1	2.35	(4,4,3,2,5,5); rough estimation based on material input
	Nitrogen oxides	-	-	kg	2.60E+1	1	1.90	(4,4,3,2,4,5); estimation based on input and emission treatment
	Ammonia	-	-	kg	4.00E+0	1	1.70	(4,4,3,2,4,5); estimation based on input and emission treatment
	Heat, waste	-	-	MJ	3.43E+4	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand
emission water, river	Chloride	-	-	kg	8.50E+1	1	3.79	(4,4,3,2,5,5); rough estimation based on material input

3.9 Maintenance SOFC fuel cell 125kW$_{el}$

3.9.1 Technical Characteristics

The dataset representing the maintenance of the SOFC fuel cell system includes the estimated material use and transport services for these activities.

SOFC fuel cells have the potential for low maintenance costs because they have few moving parts. Routine maintenance mainly includes ancillary systems such as replacement of the desulphurisation catalyst, filter replacement as well as maintenance of pumps and fans needed for operating the fuel cell system. Maintenance should be carried out annually (Siemens 2006).

Major overhaul of the fuel cell system involves the replacement of the stack. The stack is expected have a lifetime between four to eight years (Knight et al., 2005). The service life of the cell stack is of primary concern for SOFC fuel cells. State-of-the-art tubular SOFC fuel cell designs have been working continuous over 69’000 hours (Fuel Cell Handbook, 2004).

3.9.2 Raw materials, energy and auxiliaries

It is assumed that maintenance will be carried out once a year (equals every 8’000 operating hours). During the annual maintenance, only minor replacement operations are carried out out (e.g. replacement of filter and desulphurisation catalyst). The amount of this additional material is estimated to be 1% of the total plant weight (= 160 kg). It is assumed to be mainly carbon steel (80%) and stainless steel (20%). In addition, the desulphurisation catalyst is replaced and the stack is replaced every sixth year during maintenance. A stack lifetime of 48'000 operating hours (equals about 40'000 hours of full-load operation) is assumed. So 1.2 kg zinc catalysts and 17% of the stack (700 kg x 0.168 = 118 kg) are replaced on average in each maintenance operation. It is assumed that the service personnel travel 200 km with a passenger car for each service. To replace the stack (every 6th year) and the other material needed for maintenances 200 km road-transport with a van is needed. This leads to an average material weight of 278 kg per maintenance. Therefore 55.6 tkm road-transport (van <3.5t) is applied for material transport.

3.9.3 Emissions to Air

Emissions to air are included in the unit processes used (e.g. transport processes). No further process-related air emissions occur.

3.9.4 Dismantling

It is assumed that all metals (160 kg) and catalyst material (1.25 kg) will be recycled. For those materials, no burdens from dismantling and recycling are included (cut-off). The dismantling of the stack is already included in the process “stack SOFC fuel cell 125kWe, future”.

3.9.5 Data quality considerations

Tab. 3.14 shows the unit process raw data and data-quality indicators of the maintenance of a SOFC fuel cell system with 125 kW$_{el}$ electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. The inventory is based on only a rough estimate for the process. Large uncertainties exist for the transport distances and the amount of material used. In general, therefore, the data quality is not very reliable.

Tab. 3.14 Unit process raw data of the maintenance of a 125kW$_{el}$ SOFC fuel cell system

	Name	Location	InfrastructureProce	Unit	maintenance SOFC fuel cell 125kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				unit			
product	maintenance SOFC fuel cell 125kWe, future	CH	0	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	1.28E+2	1	1.38	(4,5,n.A.,n.A.,1,5); estimate
	chromium steel 18/8, at plant	RER	0	kg	3.20E+1	1	1.38	(4,5,n.A.,n.A.,1,5); estimate
	zinc, primary, at plant	RER	0	kg	1.25E+0	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected lifetime of reformer catalyst
	stack SOFC fuel cell 125kWe, future	CH	1	unit	1.67E-1	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected stack lifetime in future
	transport, van <3.5t	CH	0	tkm	5.56E+1	1	2.14	(4,5,n.A.,n.A.,1,5); estimated for material and stack transport
	transport, passenger car	CH	0	pkm	2.00E+2	1	2.14	(4,5,n.A.,n.A.,1,5); estimated

3.10 Cumulative results and interpretation

3.10.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Multi-output process “natural gas, burned in SOFC fuel cell 125 kW$_{el}$, future”

The major part of the NMVOC (94%), nitrogen oxide (79%) and particulate < 2.5um emissions (42%) and the cumulative energy demand (fossil: 98%, nuclear: 28%) are caused by the natural gas used for operation. The major part of the carbon dioxide (86%) emissions are caused by direct emissions from operation. Also a small part of the nitrogen oxide (6%) emissions are caused by direct emissions. The manufacture of the fuel cell is for the nitrogen oxide (10%) and particulate < 2.5um emissions (46%) and the cumulative energy demand (fossil: 2%, nuclear: 53%) of importance. Tab. 3.15 shows selected LCI results and cumulative energy demands for electricity and heat production with a SOFC fuel cell system. The results depend significantly on the chosen allocation method.

Multi-output process “biogas, burned in SOFC fuel cell 125 kW$_{el}$, future”

The major part of the fossil carbon dioxide (89%), NMVOC (73%), nitrogen oxide (65%) and particulate < 2.5um emissions (50%) and the cumulative energy demand (biomass: 79%, fossil: 91%, nuclear: 97%) are caused by the refined biogas used for operation. A smaller part of the nitrogen oxide (10%) emissions are caused by direct emissions from operation. The manufacture of the fuel cell is for the fossil carbon dioxide (8%), NMVOC (14%), nitrogen oxide (17%) and particulate < 2.5um emissions (40%) and the cumulative energy demand (fossil: 7%, nuclear: 2%) of importance. Tab. 3.15 shows selected LCI results and cumulative energy demands for electricity and heat production with a SOFC fuel cell system. The results depend significantly on the chosen allocation method.

Process “ SOFC fuel cell 125 kW$_{el}$, future ”

The major part of the emissions and cumulative energy demand are caused by the material and energy used for the production of the auxiliary systems of the fuel cell. The fuel cell stack is for a considerable part of the fossil carbon dioxide (16%), NMVOC (21%), nitrogen oxide (26%) and particulate < 2.5um emissions (10%) responsible. Also for the cumulative energy demand (fossil: 18%, nuclear: 20%) the production of the fuel cell stack is of importance. For the NMVOC air emissions (33%) and cadmium soil emissions (83%) the production of the electronic components is an important source. Tab. 3.15 shows selected LCI results and cumulative energy demands for the manufacture of a 125 kW$_{el}$ SOFC fuel cell system.

Process “stack SOFC fuel cell 125 kW$_{el}$, future ”

The major part of the fossil carbon dioxide (38%), NMVOC (12%), nitrogen oxide (16%) and particulate < 2.5um emissions (23%) and the cumulative energy demand (fossil: 29%, nuclear: 75%) are caused by the electricity used for the stack production. Also an important part of the fossil carbon dioxide (23%), NMVOC (30%), nitrogen oxide (11%) and particulate < 2.5um emissions (26%) and the cumulative energy demand (fossil: 29%, nuclear: 11%) are caused by the lanthanum oxide used for the stack. Tab. 3.15 shows selected LCI results and cumulative energy demands for the manufacture of a 125 kW$_{el}$ SOFC fuel cell stack.

Tab. 3.15 Selected LCI results and the cumulative energy demand for a 125kW$_{el}$ SOFC fuel cell system

Ecocat	Ecosubcat	Name	Name	heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	heat, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	SOFC fuel cell 125kWe, future	stack SOFC fuel cell 125kWe, future	maintenance SOFC fuel cell 125kWe, future
			Location	CH	CH	CH	CH	CH	CH	CH
			Unit	MJ	MJ	kWh	kWh	unit	unit	unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	3.96E-01	8.72E-02	8.40E+00	1.82E+00	1.14E+06	2.10E+05	4.16E+04
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	3.00E-03	5.93E-02	5.65E-02	1.26E+00	2.74E+05	5.46E+04	1.02E+04
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	1.21E-06	9.80E-07	2.58E-05	2.08E-05	5.50E+01	5.35E+01	8.94E+00
	water	renewable energy resources, water	MJ-Eq	9.63E-04	1.24E-02	1.76E-02	2.61E-01	5.05E+04	7.86E+03	1.59E+03
	biomass	renewable energy resources, biomass	MJ-Eq	2.22E-04	5.76E-04	4.34E-03	1.19E-02	1.76E+04	3.01E+03	5.55E+02
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	5.27E-05	2.24E-04	1.02E-03	4.68E-03	4.72E+03	9.93E+02	1.83E+02
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	7.25E-07	6.76E-06	1.40E-05	1.43E-04	6.87E+01	1.42E+01	2.62E+00
selected LCI results	resource	land occupation	m2a	5.94E-05	1.33E-04	1.16E-03	2.72E-03	4.26E+03	3.94E+02	8.33E+01
	air	CO2, fossil	kg	2.11E-02	5.18E-03	4.48E-01	1.08E-01	7.75E+04	1.26E+04	2.56E+03
	air	NMVOC	kg	1.29E-05	2.77E-06	2.74E-04	5.73E-05	7.16E+01	1.52E+01	2.91E+00
	air	nitrogen oxides	kg	1.05E-05	6.59E-06	2.17E-04	1.34E-04	2.03E+02	5.29E+01	1.00E+01
	air	sulphur dioxide	kg	1.21E-05	1.17E-05	2.49E-04	2.41E-04	3.88E+02	4.67E+01	8.95E+00
	air	particulates, <2.5 um	kg	6.43E-07	7.26E-07	1.20E-05	1.38E-05	5.07E+01	5.12E+00	1.29E+00
	water	BOD	kg	2.93E-06	2.43E-06	5.82E-05	4.77E-05	1.45E+02	2.13E+01	4.42E+00
	soil	cadmium	kg	8.51E-13	1.40E-12	1.74E-11	2.90E-11	1.28E-04	7.57E-06	1.36E-06

3.11 Conclusions

The LCI results show that the fuel and the emissions from the operation of the SOFC fuel cell are for many elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 3.15) the production of the infrastructure is of high importance.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20-25% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are clearly higher with the use of biogas.

3.12 Appendices: EcoSpold Meta Information

Tab. 3.16 EcoSpold Meta Information of Co-generation with a 125kW$_{el}$ SOFC fuel cell system

ReferenceFunction	Name	SOFC fuel cell 125kWe, future	natural gas, burned in SOFC fuel cell 125kWe, future	biogas, burned in SOFC fuel cell 125kWe, future	stack SOFC fuel cell 125kWe, future	maintenance SOFC fuel cell 125kWe, future
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	1	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit	unit
DataSetInformatio	Type	1	5	5	1	1
	Version	2.0	2.0	2.0	2.0	2.0
	energyValues	0	0	0	0	0
	LanguageCode	en	en	en	en	en
	LocalLanguageCode	de	de	de	de	de
DataEntryBy	Person	72	72	72	72	72
	QualityNetwork	1	1	1	1	1
ReferenceFunctio	DataSetRelatesToProduct	1	1	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials, the engine delivery and the installation on site.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes the most important materials used for production. Also included is the transport of these materials and the energy needed for production.	The module includes an estimation for materials and transport used for the maintenance of the SOFC fuel cell unit.
	Amount	1	1	1	1	1
	LocalName	SOFC Brennstoffzelle 125kWel, zukünftig	Erdgas, in SOFC Brennstoffzelle 125kWel, zukünftig	Biogas, in SOFC Brennstoffzelle 125kWel, zukünftig	Zellenstapel SOFC Brennstoffzelle 125kWel, zukünftig	Wartung SOFC Brennstoffzelle 125kWel, zukünftig
	Synonyms	solid oxide fuel cell//oxidkeramische Hochtemperaturbrennstoffzelle//Festoxid Brennstoffzelle//Festkeramik Brennstoffzelle	solid oxide fuel cell//oxidkeramische Hochtemperaturbrennstoffzelle//Festoxid Brennstoffzelle//Festkeramik Brennstoffzelle	solid oxide fuel cell//oxidkeramische Hochtemperaturbrennstoffzelle//Festoxid Brennstoffzelle//Festkeramik Brennstoffzelle	solid oxide fuel cell//oxidkeramische Hochtemperaturbrennstoffzelle//Festoxid Brennstoffzelle//Festkeramik Brennstoffzelle	solid oxide fuel cell//oxidkeramische Hochtemperaturbrennstoffzelle//Festoxid Brennstoffzelle//Festkeramik Brennstoffzelle
	GeneralComment	The module reflects a solid oxide fuel cell (SOFC) system with 125 kW electrical output. Inventory based on information from literature and one manufacturer. Life time operation of auxiliary systems is 80'000 h. Stack lifetime is 48'000 h.	The multioutput-process 'natural gas, burned in SOFC fuel cell 125kWe delivers the coproducts 'heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe' and 'electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe' . The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The multioutput-process 'biogas, burned in SOFC fuel cell 125kWe delivers the coproducts 'heat, biogas, allocation exergy, at SOFC fuel cell 125kWe' and 'electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe' . The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The module reflects a solid oxide fuel cell (SOFC) stack with 125 kW electrical output. Inventory based on information from literature and one manufacturer. Life time operation of stack is 48'000h (6 years).	The module reflects the maintenance for a solid oxide fuel cell (SOFC) system with 125 kW electrical output. Inventory based on information from literature for future production based on manufacturer data. Maintenance is carried out every 8'000 h. Stack lifetime is 48'000 h. Desulpurising catalyst replacement every 8'000 h.
	InfrastructureIncluded	1	1	1	1	1
	Category	natural gas	natural gas	biomass	natural gas	natural gas
	SubCategory	cogeneration	cogeneration	cogeneration	cogeneration	cogeneration
	LocalCategory	Erdgas	Erdgas	Biomasse	Erdgas	Erdgas
	LocalSubCategory	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	2000	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005	2005
	DataValidForEntirePeriod	1	1	1	1	1
	OtherPeriodText					

Tab. 3.16 (Part 2) EcoSpold Meta Information of Co-generation with a 125kW$_{el}$ SOFC fuel cell system

ReferenceFunction	Name	SOFC fuel cell 125kWe, future	natural gas, burned in SOFC fuel cell 125kWe, future	biogas, burned in SOFC fuel cell 125kWe, future	stack SOFC fuel cell 125kWe, future	maintenance SOFC fuel cell 125kWe, future
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	1	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit	unit
Geography	Text	Process applicable in central European conditions.	Natural gas input modelled for Switzerland. Process applicable in central European conditions.	Biogas input modelled for conditions in Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.	Process applicable in central European conditions.
Technology	Text	Solid oxide fuel cell (SOFC) with unpressurised tubular stack design for central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 47%, total efficiency 80%.	Solid oxide fuel cell (SOFC) with unpressurised tubular stack design for central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 47%, total efficiency 80%. Operation as base load engine with low partial load hours.	Solid oxide fuel cell (SOFC) with unpressurised tubular stack design for central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with refined biogas from low pressure gas network. Electrical efficiency 47%, total efficiency 80%. Operation as base load engine with low partial load hours.	Solid oxide fuel cell (SOFC) with unpressurised tubular stack design for central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 47%, total efficiency 80%.	Solid oxide fuel cell (SOFC) with unpressurised tubular stack design for central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 47%, total efficiency 80%.
Representativene	Percent					
	ProductionVolume	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information
	Extrapolations	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none
DataGeneratorAn	Person	72	72	72	72	72
	DataPublishedIn	2	2	2	2	2
	ReferenceToPublishedSource	47	47	47	47	47
	Copyright	1	1	1	1	1
	AccessRestrictedTo	0	0	0	0	0
	CompanyCode					
	CountryCode					
	PageNumbers	SOFC fuel cell	SOFC fuel cell	SOFC fuel cell	SOFC fuel cell	SOFC fuel cell
ProofReading	Validator	42	42	42	42	42
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none	none	none

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4 SOFC-GT fuel cell

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Last changes: 10.12.2007

4.1 Introduction

Solid **O**xide **F**uel **C**ells **G**as **T**urbine Hybrid Systems (SOFC-GT) are developed in order to achieve higher efficiencies than with a SOFC fuel cell alone. The efficiency of solid oxide fuel cells increases with increasing operating pressure. A SOFC fuel cell operating at elevated pressure combined with a gas turbine (or micro gas turbine for smaller units) leads to an elevated efficiency of the total system. An overall electrical efficiency of 70 percent should be possible with such systems at 2-3 MW capacity (Adamson 2006).

Since the combined cycle system with a SOFC fuel cell and a micro gas turbine can achieve levels of efficiency comparable to efficiencies of large gas combined cycle system at a capacity two orders of magnitude smaller than non-fuel cell systems. These systems are therefore of interest for distributed power generation.

4.2 Characterisation of material product

SOFC-GT fuel cell systems are still in development. As a proof of concept Siemens Power Generation operated a 200 kW_{el} SOFC-GT fuel cell systems in field tests. Various manufacturers work on SOFC-GT fuel cell systems including Siemens Power Generation, Mitsubishi Heavy Industries, Rolls Royce and Ztek (Adamson 2006).

4.3 Use / application of product

SOFC-GT fuel cell systems have an excellent electrical efficiency. Because of their complexity and their long start up time they are more suitable for larger co-generation applications (> $100kW_{el}$) where not many start ups will occur. Because of the high electrical efficiency, SOFC-GT fuel cell systems may also be used for power generation only (without heat recovery). Such plants are studied for applications with up to $100MW_{el}$.

So far SOFC-GT fuel cell systems are designed for operation on conventional fuels such as natural gas or propane. The high operating temperature of SOFC fuel cells makes them suitable for biogas or other liquid fuels such as kerosene or diesel. Also system designs operating with gasified coal are under development. Only systems for co-generation applications operated with natural gas (or biogas in natural gas quality) are investigated.

4.4 System characterisation

Fig. 4.1 shows the system outline of the modelled SOFC-GT fuel cell system. It is assumed that the turbine is connected to the Swiss and European low-pressure gas network (Faist Emmenegger et al. 2003). Natural gas (Faist Emmenegger et al. 2003) and biogas (Jungbluth et al. 2007) are included as energy carriers to operate the SOFC-GT fuel cell system.

Natural gas (or biogas in natural gas quality) is the primary fuel of choice for residential co-generation applications. The operation of SOFC fuel cell system with low calorific gases such as landfill gas or digester gas is also possible if the desulphurisation system is adapted to the biogas composition. So far no field-tests with raw biogas are carried out. SOFC-GT fuel cell systems operated with raw biogas drawn directly from the production site (e.g. an agricultural site or waste water plant) are not considered in this inventory.

A dataset of the heat production corresponding to each electricity dataset is also provided. Electricity production is given in kWh, heat production in MJ. It is assumed that the SOFC-GT fuel cell system is operated in Switzerland (CH). However, the process is applicable also for central European conditions.

The infrastructure dataset refers to a 125 kWel SOFC fuel cell and a 55 kW_{el} micro gas turbine. The infrastructure dataset includes a 125 kW_{el} SOFC fuel cell system with tubular cell design (Siemens 2006, Karakoussis et al. 2000) and a 100 kW_{el} micro gas turbine available on the market around year 2005 (Turbec 2005, Nadal 1997). The performance data for operation and the stack operating life are based on actual target values specified by the manufacturer. These values may not yet be reached but this is likely to happen within the next years. The emission levels used in the datasets are based on test data and target values specified by the manufacturer.

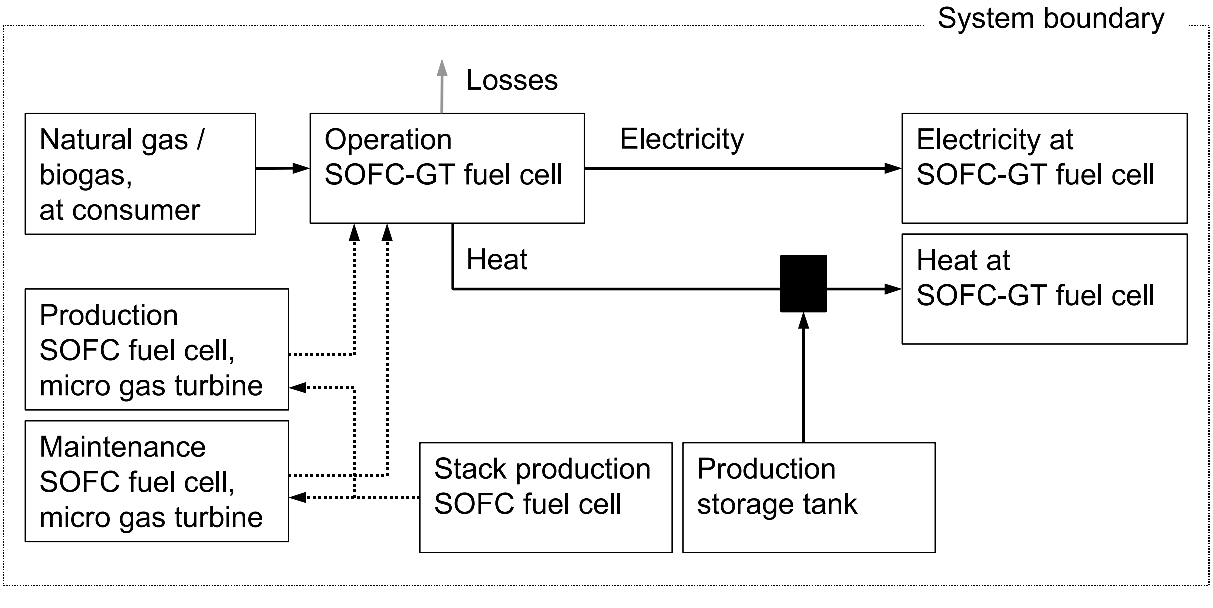

Fig. 4.1 **System outline of a 180 kW_{el} SOFC-GT fuel cell system**

4.5 Natural gas, burned in SOFC-GT fuel cell 180 kW_{el}

4.5.1 Technical Characteristics

A large pressurised SOFC-GT hybrid fuel cell system with 180 kW_{el} and 70 kW_{th} is analysed. An electrical efficiency of 52% (LHV) is demonstrated by Siemens Power Generation with a 200 kW_{el} pressurized SOFC-GT system (Frey 2005). For SOFC fuel cell systems with a power capacity of about 200 kW_{el} the target values of the electrical efficiencies (based on LHV) range between 55 and 63 percent and total efficiencies of around 80 percent (Adamson 2006, Kimijima and Kasagi 2002, Krewitt et al. 2004, Williams et al. 2001). For larger systems with 2-3 MW_{el} capacity an electrical efficiency of 70 percent is expected (Adamson 2006).

In a typical SOFC-GT plant design the micro gas turbine has a share of 20 to 40 percent of the power output (Kimijima and Kasagi 2002, Williams et al. 2001). A system with a 125 kW_{el} SOFC fuel cell (70%) and a 55 kW_{el} micro gas turbine (30%) is used for this inventory.

SOFC fuel cells have a excellent partial-load operation efficiency. Similar to other fuel cell systems the cell stack efficiency improves at lower loads, resulting in an slight increase in the electrical efficiency of the system (Knight et al., 2005). It is expected that SOFC-GT systems can keep the electrical efficiency above 60 percent in the range of 50 to 100 percent of the nominal load (Kimijima and Kasagi 2002). An average electrical efficiency of 48 percent and a total efficiency of 80 percent are assumed for the operation of the pressurised 180 kW_{el} SOFC-GT fuel cell hybrid system (see Tab. 4.1). The performance values used here are based on target values for serial products and are already reached in field tests.

Tab. 4.1 Electric and thermal efficiencies and losses of a 180kW_{el} SOFC-GT fuel cell system

Electricity generation	MJ/MJ_{in}	0.58
Heat generation	MJ/MJ_{in}	0.22
Total energy output	MJ/MJ_{in}	0.80
Heat losses	MJ/MJ_{in}	0.20
Waste heat, total *)	MJ/MJ_{in}	0.521
*) Based on HHV; natural gas, CH, low pressure: HHV 40.2 MJ/Nm^3; LHV = 36.5 MJ/Nm^3 and including losses as well as heat generated		

4.5.2 Equipment and maintenance needed

The hybrid SOFC fuel cell gas turbine system a similar life time as for the SOFC fuel cell system is used. For the calculations a life time of 80'000 hours (full and partial load hours) with 9 maintenance sessions during the life time (maintenance every 8'000 hours) is assumed. The maintenance of the fuel cell system includes also periodical catalyst and stack replacement (see SOFC fuel cell section).

For the operation of the SOFC-GT fuel cell an average load factor similar to the operation of a 100 kW_{el} micro gas turbine is used. An average load factor of 81% is assumed. The fuel consumption is 310 kW at nominal load. Maintenance is needed every 8.04 TJ_{In} of fuel input, and the operating life of the unit is reached after 72.4 TJ_{In} of fuel input.

Besides the infrastructure of the SOFC fuel cell unit, a storage tank is needed to ensure good system performance. A storage volume of 8 m^3 is assumed. The inventory of the storage tank is based on the 10 m^3 storage tank described in Heck (2003). As in Heck (2003), the operating life of the storage tank is 100’000 hours or 90.5 TJ_{In} of fuel input.

A gas boiler for peak load and backup is used in order to reach a long operating period at full load. Depending on the variability of the heat requirement, this boiler is able to deliver up to 80% of the peak load. The gas boiler for peak load or backup is not included in this inventory because the system design depends strongly on the specific application.

The infrastructure processes included are summarised in Tab. 4.2.

Tab. 4.2 Equipment and maintenance of the SOFC-GT fuel cell system operated with natural gas

Process	Operating life, interval	Amount
SOFC-GT fuel cell 180kWe, future	80'000 h	1.38 E-8 units/MJin
Maintenance of SOFC-GT fuel cell 180kWe, future	9 times per 80'000 h	1.24 E-7 units/MJin
Storage 10'000 l , *)	100'000 h	9.83 E-9 units/MJin
*) For 8 m^3 storage size 0.89 units are used.		

4.5.3 Energy and auxiliaries usage

Natural gas consumption

The technical characteristics described in Section 3.5.1 specify the use of natural gas from the Swiss low-pressure gas network. According to Faist Emmenegger et al. (2003), the gas has a lower heating value of 36.5 MJ/Nm^3 and a higher heating value of 40.2 MJ/Nm^3.

Water and lubricant consumption

For each start up the SOFC fuel cell units needs 0.15 m^3 of filtered potable tap water (Siemens, 2006). During operation no additional water is needed. Because each start up of the unit takes up to 18 hours and reduces the stack lifetime, continuos operation must be achieved. Therefore only one start up every 8’000 hours for maintenance is assumed. The additional water consumption is therefore $2.4*10^{-5}$ kg/MJ_{In}.

A 100 kW_{el} micro gas turbine has a lubricant consumption of 3 litres per 6000 operating hours (Turbec, 2005), For the SOFC-GT fuel cell system with a 55 kW_{el} micro gas turbine this equals 0.17 mg/MJ_{In} (calculated with an average load factor of 81% and a fuel consumption of the micro gas turbine of 190 kW at nominal load).

4.5.4 Emissions to Air

No specific emission value for SOFC-GT fuel cell systems are available. Therefore the emission values of the 125 kW_{el} SOFC fuel cell and the 100 kW_{el} micro gas turbine are used for the calculations. For all emissions except the nitrogen oxides (NOx) emissions the values of the SOFC fuel cell are used, because the micro gas turbine is situated in the exhaust gas of the fuel cell. For the NOx emission it is possible that higher emissions occur after the turbine due to higher temperatures in the gas turbine. For the NOx emission it is assumed that the emission level rises with a rising power share of the gas turbine (from 2 to 11 mg/MJ_{In} in this case). The emission values used for operation with natural gas are summarised in Tab. 4.3.

Tab. 4.3 Emissions to air of SOFC-GT fuel cell systems operated with natural gas

Emission values	**CO_2**	**NOx**	**CO**	**NMVOC**	**CH4**	**PM 2.5**	**SO_2**	**N_2O**
	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}	mg/MJ_{In}
SOFC fuel cell, 125 kW_{el}	56	2	1.7	0.7	4.0	0	0.55	0
Micro gas turbine, 100 kW_{el}	56	32	28	0.6	5.4	0.5	0.55	1
SOFC-GT fuel cell system	**56**	**11**	**1.7**	**0.7**	**4.0**	**0**	**0.55**	**0**

4.5.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- Heat, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future
- Electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is applied in this project. An allocation based on exergy leads to higher specific requirements and emissions per kWh of electricity compared to 1 kWh of heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 4.4.

Tab. 4.4 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	58 %	22 %	80 %
Exergy factor *)	1.000	0.170	-
Allocation factor	94.0 %	6.0 %	100.0 %
*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production			

4.5.6 Data quality considerations

Tab. 4.5 shows the multi-output process raw data and data-quality indicators of the inventory of natural gas, burned in SOFC-GT fuel cell 180kWe, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such plants. Because these systems have so far operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached within the next 5 years with a serial product.

Tab. 4.5 Multi-output process raw data of natural gas, burned in SOFC-GT fuel cell 180 kW$_{el}$, future

	Name	Location	InfrastructureProcess	Unit	natural gas, burned in SOFC-GT fuel cell 180kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	CH	0	MJ	2.20E-1				100	0
	electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	CH	0	kWh	1.61E-1				0	100
technosphere	SOFC-GT fuel cell 180kWe, future	CH	1	unit	1.38E-8	1	1.14	(2,3,2,1,1,4); uncertainty of life time	6.0	94.0
	maintenance SOFC-GT fuel cell 180kWe, future	CH	0	unit	1.24E-7	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	6.0	94.0
	storage 10'000 l	RER	1	unit	9.83E-9	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	natural gas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	6.0	94.0
	tap water, at user	CH	0	kg	2.10E-5	1	1.26	(3,4,2,2,1,5); company data	6.0	94.0
	lubricating oil, at plant	RER	0	kg	1.70E-7	1	1.17	(3,3,2,1,1,4); company data for 100kWel micro gas turbine	6.0	94.0
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.87E-7	1	1.31	(4,3,2,1,1,5); calculated from oil input	6.0	94.0
emission air, high population density	Carbon dioxide, fossil	-	-	kg	5.60E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	6.0	94.0
	Carbon monoxide, fossil	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on fuel cell references	6.0	94.0
	Methane, fossil	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on fuel cell references	6.0	94.0
	Nitrogen oxides	-	-	kg	1.10E-5	1	1.67	(4,5,2,1,1,5); estimate based on fuel cell and micro gas turbine references	6.0	94.0
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	7.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on fuel cell references	6.0	94.0
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	6.0	94.0
	Heat, waste	-	-	MJ	5.21E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	6.0	94.0

4.6 Biogas gas, burned in SOFC-GT fuel cell 180 kW_{el}, future

4.6.1 Technical Characteristics

The operation of SOFC-GT fuel cell systems with low-calorific gases such as landfill gas and digester gas are not considered. PEM fuel-cell systems operated with raw biogas drawn directly from the production site (e.g. agricultural site or waste water plant) are not considered in this inventory. Only biogas distributed in the regular natural gas network is considered. This biogas has a quality similar to natural gas. The content of methane must be at least 96 vol-%.

Tab. 4.6 Electric and thermal efficiencies and losses of a 180kW_{el} SOFC-GT fuel cell system

Electricity generation	MJ/MJ_{in}	0.58
Heat generation	MJ/MJ_{in}	0.22
Total energy output	MJ/MJ_{in}	0.80
Heat losses	MJ/MJ_{in}	0.20
Waste heat, total *)	MJ/MJ_{in}	0.527
*) Based on HHV; biogas, CH, high pressure: HHV 38.146 MJ/Nm^3; LHV = 34.450 MJ/Nm^3 and including losses as well as heat generated		

4.6.2 Equipment and maintenance needed

The infrastructure size needed is identical to that of the engines operated with natural gas presented in Section 3.5.2 (Tab. 4.2). An operating life of 80'000 hours with nine maintenance sessions during this period is assumed. Maintenance is needed every 8.04 TJ_{In} of fuel input and the full operating life of the unit is reached after 72.4 TJ_{In} of fuel input. As in the unit operated with natural gas, a storage tank volume of 8 m^3 is assumed, which has to be replaced after every 90.5 TJ_{In} of fuel input. An average load factor of 81% is assumed as defined for operation with natural gas.

4.6.3 Energy and auxiliaries usage

Biogas consumption

The distribution requirements (energy, leakages) are similar to those of natural gas. Only the composition of the emissions differs due to the different compositions of biogas and natural gas. The dataset "methane, 96 vol-%, from biogas, low pressure, at consumer" is used as the process input for the SOFC-GT fuel cell system. According to Jungbluth et al. (2007), the gas has a lower heating value of 34.45 MJ/Nm^3 and a higher heating value of 38.15 MJ/Nm^3. On the basis of the lower heating value,

Water and lubricant consumption

As for the operation with natural gas an additional water consumption of $2.1*10^{-8}$ m^3/MJ_{In} for the fuel cell start ups is included. The micro gas turbine in the SOFC-GT fuel cell system has a lubricant consumption of 0.17 mg/MJ_{In}.

4.6.4 Emissions to Air

The biogenic CO_2 emissions are calculated on the basis of the carbon content of the biogas mix. The values presented in Tab. 4.7 also take into account carbon emitted in the form of CO, CH_4 and NMVOC. For the operation of the SOFC-GT fuel cell system with refined biogas, identical emission factors are used to those for operation with natural gas (see Section 3.5.4).

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. The H_2S content in odorated natural gas is similar to that of the biogas presented in Jungbluth (2007). Because sulphur is toxic to the catalysts used, it is removed by a catalytic reaction before entering the fuel processing unit. The SO_2 emissions therefore do not occur during operation but when the catalyst is regenerated. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied here.

Tab. 4.7 CO_2-emissions and carbon balance

	Emission factor	Carbon content	Share
Biogas input	-	524'992.3 mg C / Nm^3 15'239.3 mg C / MJ_{In}	100.00 %
Carbon dioxide, biogenic	55'823.0 mg/MJ_{In}	15'235.0 mg C / MJ_{In}	99.97 %
Carbon monoxide, biogenic	1.7 mg/MJ_{In}	0.7 mg C / MJ_{In}	0.01 %
Methane, biogenic	4 mg/MJ_{In}	3.0 mg C / MJ_{In}	0.02 %
NMVOC *)	0.7 mg/MJ_{In}	0.6 mg C / MJ_{In}	0.00 %
*) Carbon content calculated as C5H12 (Pentane)			

4.6.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- Heat, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future
- Electricity, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is used in this project. Allocations based on exergy lead to higher specific requirements and emissions per kWh of electricity compared to 1 kWh heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 4.8.

Tab. 4.8 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	58 %	22 %	80 %
Exergy factor *)	1.000	0.170	-
Allocation factor	94.0 %	6.0 %	100.0 %
*) Based on a hot water temperature of 90/70 °C and an ambient temperature of 20 °C for heat production			

4.6.6 Data quality considerations

Tab. 4.9 shows the multi-output process raw data and data-quality indicators of the inventory of biogas, burned in SOFC-GT fuel cell 180kWe, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far operated only under test conditions, the performance data are based on filed test data and target values (efficiency) or approximations (emissions) which are expected to be reached within the next 5 years.

Tab. 4.9 Multi-output process raw data of biogas, burned in SOFC-GT fuel cell 180 kW_{el}, future

	Name	Location	InfrastructureProcess	Unit	biogas, burned in SOFC-GT fuel cell 180kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	electricity, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	CH	0	MJ	2.20E-1				100	0
	electricity, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe, future	CH	0	kWh	1.61E-1				0	100
technosphere	SOFC-GT fuel cell 180kWe, future	CH	1	unit	1.38E-8	1	1.14	(2,3,2,1,1,4); uncertainty of life time	6.0	94.0
	maintenance SOFC-GT fuel cell 180kWe, future	CH	0	unit	1.24E-7	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	6.0	94.0
	storage 10'000 l	RER	1	unit	9.83E-9	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	6.0	94.0
	tap water, at user	CH	0	kg	2.10E-5	1	1.26	(3,4,2,2,1,5); company data	6.0	94.0
	lubricating oil, at plant	RER	0	kg	1.70E-7	1	1.17	(3,3,2,1,1,4); company data for 100kWel micro gas turbine	6.0	94.0
	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	1.87E-7	1	1.31	(4,3,2,1,1,5); calculated from oil input	6.0	94.0
emission air, high population	Carbon dioxide, biogenic	-	-	kg	5.58E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of biogas	6.0	94.0
	Carbon monoxide, biogenic	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on fuel cell references	6.0	94.0
	Methane, biogenic	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on fuel cell references	6.0	94.0
	Nitrogen oxides	-	-	kg	1.10E-5	1	1.67	(4,5,2,1,1,5); estimate based on fuel cell and micro gas turbine references	6.0	94.0
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	7.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on fuel cell references	6.0	94.0
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	6.0	94.0
	Heat, waste	-	-	MJ	5.27E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	6.0	94.0

4.7 Manufacture of a SOFC-GT fuel cell 180kW$_{el}$

4.7.1 Technical Characteristics

The infrastructure module for the 180 kW$_{el}$ SOFC-GT fuel cell unit includes a 125 kW$_{el}$ SOFC fuel cell and an estimation for a 55 kW$_{el}$ micro gas turbine. The infrastructure dataset includes the most important materials used for production, the transport of these materials and the energy needed for production and engineering.

The infrastructure needed is defined by the total operating life and the maintenance intervals of the unit. The expected life time of a SOFC fuel cell unit lies between 40'000 and 100'000 operating hours (Frey 2005, DEA 2005, Pehnt 2002). The life time of a micro turbine lies between 45'000 and 60'000 operating hours and the maintenance interval between 6'000 and 12'000 hours (Turbec 2005, Ohkubo 2006). An operating life of 80'000 hours for the SOFC fuel cell, 50'000 hours for the micro gas turbine and a maintenance interval of 8'000 hours is assumed. The maintenance of the fuel cell system includes also periodical catalyst and stack replacement (see SOFC fuel cell section).

4.7.2 Infrastructure processes used Equipment and maintenance needed

The infrastructure needed is defined by the total operating life of the unit. The expected operating life time of a SOFC fuel cell unit lies between 40'000 and 100'000 hours (Frey 2005, DEA 2005, Pehnt 2002). The operating life time of a micro turbine lies between 45'000 and 60'000 hours (Turbec 2005, Ohkubo 2006). For the calculations a life time of 80'000 hours for the SOFC fuel cell and of 50'000 hours for the micro gas turbine is used.

For the calculations a operating life time of 80'000 hours is used for the 180 kW$_{el}$ SOFC-GT system. The micro gas turbine has to be replaced once during the operating life time of the unit. A smaller micro gas turbine (55 kW$_{el}$) is needed than the one to which the inventory correspond (100 kW$_{el}$). Due to the almost linear dependence between nominal electrical power and the weight of the micro gas turbine unit, only 55% of the amount is needed. Because of the shorter life time of the micro gas turbine the 180 kW$_{el}$ SOFC-GT system requires one micro gas turbine unit of the 100 kW$_{el}$ to cover the whole lifetime of 80'000 hours.

4.7.3 Dismantling

After their service life SOFC-GT fuel cells are dismantled and the materials recycled or disposed of. It is assumed that all metals and catalyst material (zinc, nickel) will be recycled. For those materials no burdens from dismantling and recycling is included (cut-off). For the ceramic materials (1257 kg, thereof 669 kg from the SOFC stack) a final disposal on a inert material landfill and for the plastic materials (60 kg) a final disposal in a municipal incineration plant is assumed. The dismantling is included in the infrastructure processes used.

4.7.4 Data quality considerations

Tab. 4.10 shows the unit process raw data and data-quality indicators of the manufacture and disposal of a SOFC-GT fuel cell unit with 180 kW$_{el}$ electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as is as well calculated from data of a larger gas turbine system than used in this inventory.

Tab. 4.10 Unit process raw data of the manufacture of a 180kW$_{el}$ SOFC-GT fuel cell system

	Name	Location	InfrastructureProc	Unit	SOFC-GT fuel cell 180kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	SOFC-GT fuel cell 180kWe, future	CH	1	unit	1			
technosphere	SOFC fuel cell 125kWe, future	CH	1	unit	1.00E+0	1	1.05	(nA.,nA.,nA.,nA.,1,nA.); material
	micro gas turbine 100kWe	CH	1	unit	1.00E+0	1	1.21	(nA.,nA.,nA.,nA.,3,nA.); input, data of 100kWel unit used for 55kWel plant

4.8 Maintenance SOFC-GT fuel cell 180kW$_{el}$

4.8.1 Technical Characteristics

The module for the maintenance of the SOFC-GT fuel cell system includes an estimated material use and transport services for these activities. The maintenance process for the 180 kW$_{el}$ SOFC-GT fuel cell unit includes the maintenance of the 125 kW$_{el}$ SOFC fuel cell and an estimation for the maintenance of the 55 kW$_{el}$ micro gas turbine.

4.8.2 Maintenance processes used

It is assumed that maintenance is carried out once a year or every 8’000 operating hours. During the regular maintenance only minor replacement jobs will be carried out (e.g. replacement of filter and desulphurisation catalyst). During periodic overhauls also other parts of the plant will are replaced.

The service life of the SOFC fuel cell is assumed with 48'000 operating hours (equals about 40'000 hours of full-load operation). About every 30’000h an overhaul of the micro turbine is required.

For the 180 kW$_{el}$ SOFC-GT fuel cell unit a smaller micro gas turbine (55 kW$_{el}$) is required as the one described in the inventory (100 kW$_{el}$). Due to the almost linear dependence between nominal electrical power and the weight of the micro gas turbine unit only 55% of the gas turbine maintenance is accounted.

4.8.3 Data quality considerations

Tab. 4.11 shows the unit process raw data and data-quality indicators of the maintenance of a SOFC-GT fuel cell system with 180 kW$_{el}$ electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. The inventory is based on only a rough estimate for the process. The process is calculated from data of a larger gas turbine system than used in the inventory. Thus in general the data quality is not very reliable..

Tab. 4.11 Unit process raw data of the maintenance of a 180kW$_{el}$ SOFC-GT fuel cell system

	Name	Location	InfrastructureProc	Unit	maintenance SOFC-GT fuel cell 180kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				unit			
product	maintenance SOFC-GT fuel cell 180kWe, future	CH	0	unit	1			
technosphere	maintenance SOFC fuel cell 125kWe, future	CH	0	unit	1.00E+0	1	1.05	(nA.,nA.,nA.,nA.,1,nA.); material
	maintenance micro gas turbine 100kWe	CH	0	unit	5.50E-1	1	1.21	(nA.,nA.,nA.,nA.,3,nA.); input, data of 100kWel unit used for 55kWel plant

4.9 Cumulative results and interpretation

4.9.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Multi-output process “natural gas, burned in SOFC-GT fuel cell 180 kW$_{el}$, future”

The major part of the NMVOC (95%), nitrogen oxide (61%) and particulate < 2.5um emissions (41%) and the cumulative energy demand (fossil: 98%, nuclear: 29%) are caused by the natural gas used for operation. The major part of the carbon dioxide (86%) emissions are caused by direct emissions from operation. Also a substantial part of the nitrogen oxide (27%) emissions are caused by direct emissions. The manufacture of the fuel cell is for the nitrogen oxide (8%) and particulate < 2.5um emissions (48%) and the cumulative energy demand (fossil: 2%, nuclear: 54%) of importance. Tab. 4.12 shows selected LCI results and cumulative energy demands for electricity and heat production with a SOFC-GT fuel cell system. The results depend significantly on the chosen allocation method.

Multi-output process “biogas, burned in SOFC-GT fuel cell 180 kW$_{el}$, future”

The major part of the fossil carbon dioxide (89%), NMVOC (73%), nitrogen oxide (45%) and particulate < 2.5um emissions (49%) and the cumulative energy demand (biomass: 80%, fossil: 91%, nuclear: 97%) are caused by the refined biogas used for operation. A large part of the nitrogen oxide (39%) emissions are caused by direct emissions from operation. The manufacture of the fuel cell is for the fossil carbon dioxide (8%), NMVOC (13%), nitrogen oxide (12%) and particulate < 2.5um emissions (42%) and the cumulative energy demand (fossil: 7%, nuclear: 2%) of importance. Tab.

4.12 shows selected LCI results and cumulative energy demands for electricity and heat production with a SOFC-GT fuel cell system. The results depend significantly on the chosen allocation method.

Process “ SOFC-GT fuel cell 180 kW$_{el}$, future ”

The major part of the fossil carbon dioxide (84%), NMVOC (89%), nitrogen oxide (84%) and particulate < 2.5um emissions (80%) and the cumulative energy demand (fossil: 84%, nuclear: 85%) are caused by the manufacture of the SOFC fuel cell. The manufacture of the micro gas turbine is with 10-20% of the emissions and cumulative energy demand of minor importance. Tab. 4.12 shows selected LCI results and cumulative energy demands for the manufacture of a 180 kW$_{el}$ SOFC-GT fuel cell system.

Tab. 4.12 Selected LCI results and the cumulative energy demand of a 180kW$_{el}$ SOFC-GT fuel cell system

Ecocat	Ecosubcat	Name	Name	heat, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	heat, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, natural gas, allocation exergy, at SOFC fuel cell 125kWe, future	electricity, biogas, allocation exergy, at SOFC fuel cell 125kWe, future	SOFC-GT fuel cell 180kWe, future	maintenance SOFC-GT fuel cell 180kWe, future
			Location	CH	CH	CH	CH	CH	CH
			Unit	MJ	MJ	kWh	kWh	unit	unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	3.96E-01	8.72E-02	8.40E+00	1.82E+00	1.35E+06	4.31E+04
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	3.00E-03	5.93E-02	5.65E-02	1.26E+00	3.21E+05	1.05E+04
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	1.21E-06	9.80E-07	2.58E-05	2.08E-05	5.52E+01	8.94E+00
	water	renewable energy resources, water	MJ-Eq	9.63E-04	1.24E-02	1.76E-02	2.61E-01	6.21E+04	1.66E+03
	biomass	renewable energy resources, biomass	MJ-Eq	2.22E-04	5.76E-04	4.34E-03	1.19E-02	1.98E+04	5.68E+02
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	5.27E-05	2.24E-04	1.02E-03	4.68E-03	5.43E+03	1.87E+02
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	7.25E-07	6.76E-06	1.40E-05	1.43E-04	7.92E+01	2.69E+00
selected LCI results	resource	land occupation	m2a	5.94E-05	1.33E-04	1.16E-03	2.72E-03	4.94E+03	8.79E+01
	air	CO2, fossil	kg	2.11E-02	5.18E-03	4.48E-01	1.08E-01	9.20E+04	2.66E+03
	air	NMVOC	kg	1.29E-05	2.77E-06	2.74E-04	5.73E-05	8.07E+01	2.99E+00
	air	nitrogen oxides	kg	1.05E-05	6.59E-06	2.17E-04	1.34E-04	2.41E+02	1.03E+01
	air	sulphur dioxide	kg	1.21E-05	1.17E-05	2.49E-04	2.41E-04	4.55E+02	9.36E+00
	air	particulates, <2.5 um	kg	6.43E-07	7.26E-07	1.20E-05	1.38E-05	6.34E+01	1.37E+00
	water	BOD	kg	2.93E-06	2.43E-06	5.82E-05	4.77E-05	1.68E+02	4.60E+00
	soil	cadmium	kg	8.51E-13	1.40E-12	1.74E-11	2.90E-11	1.31E-04	1.39E-06

4.10 Conclusions

The LCI results show that the fuel and the emissions from the operation of the SOFC-GT fuel cell are for many elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 4.12) the production of the infrastructure is of high importance.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20-25% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are clearly higher with the use of biogas.

4.11 Appendices: EcoSpold Meta Information

Tab. 4.13 EcoSpold meta information for co-generation with a 180kW$_{el}$ SOFC-GT fuel cell system

ReferenceFunction	Name	SOFC-GT fuel cell 180kWe, future	natural gas, burned in SOFC-GT fuel cell 180kWe, future	biogas, burned in SOFC-GT fuel cell 180kWe, future	maintenance SOFC-GT fuel cell 180kWe, future
Geography	Location	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit
DataSetInformatio	Type	1	5	5	1
	Version	2.0	2.0	2.0	2.0
	energyValues	0	0	0	0
	LanguageCode	en	en	en	en
	LocalLanguageCode	de	de	de	de
DataEntryBy	Person	72	72	72	72
	QualityNetwork	1	1	1	1
ReferenceFunctio	DataSetRelatesToProduct	1	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials, the engine delivery and the installation on site.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes an estimation for materials and transport used for the maintenance of the hybrid SOFC-GT fuel cell micro gas turbine unit.
	Amount	1	1	1	1
	LocalName	SOFC-GT Brennstoffzelle 180kWel, zukünftig	Erdgas, in SOFC-GT Brennstoffzelle 180kWel, zukünftig	Biogas, in SOFC-GT Brennstoffzelle 180kWel, zukünftig	Wartung SOFC-GT Brennstoffzelle 180kWel, zukünftig
	Synonyms	solid oxide fuel cell hybrid cycle power system//SOFC gas turbine hybrid//SOFC Gasturbinen Hybridsystem//Festoxid Brennstoffzellen Gasturbinen Hybridsystem	solid oxide fuel cell hybrid cycle power system//SOFC gas turbine hybrid//SOFC Gasturbinen Hybridsystem//Festoxid Brennstoffzellen Gasturbinen Hybridsystem	solid oxide fuel cell hybrid cycle power system//SOFC gas turbine hybrid//SOFC Gasturbinen Hybridsystem//Festoxid Brennstoffzellen Gasturbinen Hybridsystem	solid oxide fuel cell hybrid cycle power system//SOFC gas turbine hybrid//SOFC Gasturbinen Hybridsystem//Festoxid Brennstoffzellen Gasturbinen Hybridsystem
	GeneralComment	The module reflects a hybrid solid oxide fuel cell (SOFC) micro gas turbine system with 180 kW electrical output. Inventory based on information from literature and one manufacturer. Life time operation of auxiliary systems is 80'000 h. Stack lifetime is 48'000 h. Lifetime of the micro gas turbine is 50'000 h.	The multioutput-process 'natural gas, burned in SOFC-GT fuel cell 180kWe delivers the coproducts 'heat, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe' and 'electricity, natural gas, allocation exergy, at SOFC-GT fuel cell 180kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The multioutput-process 'biogas, burned in SOFC-GT fuel cell 180kWe delivers the coproducts 'heat, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe' and 'electricity, biogas, allocation exergy, at SOFC-GT fuel cell 180kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The module reflects the maintenance for a hybrid solid oxide fuel cell (SOFC) micro gas turbine system with 180 kW electrical output. Inventory based on information from literature and one manufacturer. Life time for operation of auxiliary systems 80'000 h, stack lifetime 48'000 h. Maintenance is carried out every 8000 h. Desulpurising catalyst replacement every 8'000 h.
	InfrastructureIncluded	1	1	1	1
	Category	natural gas	natural gas	biomass	natural gas
	SubCategory	cogeneration	cogeneration	cogeneration	cogeneration
	LocalCategory	Erdgas	Erdgas	Biomasse	Erdgas
	LocalSubCategory	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)
	Formula				
	StatisticalClassification				
	CASNumber				
TimePeriod	StartDate	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005
	DataValidForEntirePeriod	1	1	1	1
	OtherPeriodText				

Tab. 4.13 (Part 2) EcoSpold meta information for co-generation with a 180kW$_{el}$ SOFC-GT fuel cell system

ReferenceFunction	Name	SOFC-GT fuel cell 180kWe, future	natural gas, burned in SOFC-GT fuel cell 180kWe, future	biogas, burned in SOFC-GT fuel cell 180kWe, future	maintenance SOFC-GT fuel cell 180kWe, future
Geography	Location	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit
Geography	Text	Process applicable in central European conditions.	Natural gas input modelled for Switzerland. Process applicable in central European conditions.	Biogas input modelled for Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.
Technology	Text	Hybrid system combining a 125 kWe solid oxide fuel cell (SOFC) with tubular stack design and a 55kWe micro gas turbine. For central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 58%, total efficiency 80%.	Hybrid system combining a 125 kWe solid oxide fuel cell (SOFC) with tubular stack design and a 55kWe micro gas turbine. For central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 58%, total efficiency 80%. Operation as base load engine with low partial load hours.	Hybrid system combining a 125 kWe solid oxide fuel cell (SOFC) with tubular stack design and a 55kWe micro gas turbine. For central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 58%, total efficiency 80%. Operation as base load engine with low partial load hours.	Hybrid system combining a 125 kWe solid oxide fuel cell (SOFC) with tubular stack design and a 55kWe micro gas turbine. For central cogeneration use. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 58%, total efficiency 80%.
Representativene	Percent				
	ProductionVolume	unknown	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information
	Extrapolations	none	none	none	none
	UncertaintyAdjustments	none	none	none	none
DataGeneratorAn	Person	72	72	72	72
	DataPublishedIn	2	2	2	2
	ReferenceToPublishedSource	47	47	47	47
	Copyright	1	1	1	1
	AccessRestrictedTo	0	0	0	0
	CompanyCode				
	CountryCode				
	PageNumbers	SOFC fuel cell	SOFC fuel cell	SOFC fuel cell	SOFC fuel cell
ProofReading	Validator	42	42	42	42
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none	none

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5 PEM fuel cell

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5.1 Introduction

The electrochemical conversion of hydrogen into electricity and heat takes place in a **P**olymer **E**lectrolyte **M**embrane fuel cell[2] (PEM). In order to obtain the hydrogen needed for conversion, fuel sources such as natural gas are reformed in an external reformer (e.g. steam reformer).

PEM fuel cells are currently considered to be the most highly developed form of fuel cell technology. They are now available on the market in a power range from 1 kW_{el} up to 250 kW_{el}. Small PEM fuel-cell systems (1-5 kW_{el}) for combined heat and power applications in residential areas are expected to come onto the market between 2008 and 2012 (Bine, 2004).

5.2 Characterisation of material product

Residential co-generation systems based on PEM fuel cells have now reached the demonstration stage. Units of up to 100 kW have been manufactured and tested in field tests. The vast majority of these systems are designed for operation with natural gas or propane. Their low operating temperature (typically 80°C) and favourable costs make them suitable for residential applications. Various manufacturers are currently developing PEM fuel cell systems with a power range of between 1-5 kW_{el}, including Ebara/Ballard, Vaillant/Plug Power, Viessmann, Buderus/IdaTech and Baxi Group/efc, (Bine, 2004; Fuel Cell Handbook, 2004).

5.3 Use / application of product

PEM fuel cell systems have excellent load-following characteristics and a very short start-up time. This makes them suitable for co-generation applications as well as for power generation in mobile applications (e.g. cars).

PEM fuel cells are particularly suitable for operation with pure hydrogen. Fuel processors have been developed to allow operation with conventional fuels such as natural gas and propane. A specific design permits the direct use of methanol without a fuel processor. The direct methanol fuel cell (DMFC) is suitable for portable electronic applications.

Only systems for co-generation applications operated with natural gas (or biogas in natural gas quality) are investigated here.

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[2] Also called the Proton Exchange Membrane Fuel Cell (PEMFC).

5.4 System characterisation

Fig. 5.1 shows the system outline of the modelled PEM fuel cell system. It is assumed that the turbine is connected to the Swiss and European low-pressure gas network (Faist Emmenegger et al. 2003). Natural gas (Faist Emmenegger et al. 2003) and biogas (Jungbluth et al. 2007) are included as energy carriers to operate the PEM fuel cell system.

Natural gas (or biogas in natural gas quality) is the primary fuel of choice for residential co-generation applications. It is difficult to operate PEM fuel cells with low calorific gases such as landfill gas or digester gas due to the high requirements on gas purity (especially CO impurities). PEM fuel cell systems operated with raw biogas drawn directly from the production site (e.g. agricultural site or waste water plant) are not considered in this inventory.

A dataset of the heat production corresponding to each electricity dataset is also provided. Electricity production is given in kWh, heat production in MJ. It is assumed that the PEM fuel cell system is operated in Switzerland (CH). However, the process is applicable also for central European conditions.

The infrastructure datasets refer to a serially manufactured PEM fuel cell (Krewitt et al. 2004). The performance data for operation and the stack operating life are based on actual target values specified by the manufacturer. These values may not yet be reached but this is likely to happen within the next 3-8 years. The emission levels used in the datasets are based on test data and target values specified by the manufacturer.

PEM fuel cells operate at about 80°C and are sensitive to carbon monoxide in the fuel gas. High-temperature PEM fuel cells which operate at up to 200°C are therefore currently under development. These high-temperature systems will not need hydrogen purification and consequently have a less complex system design. However, only low-temperature PEM fuel cell systems are investigated here.

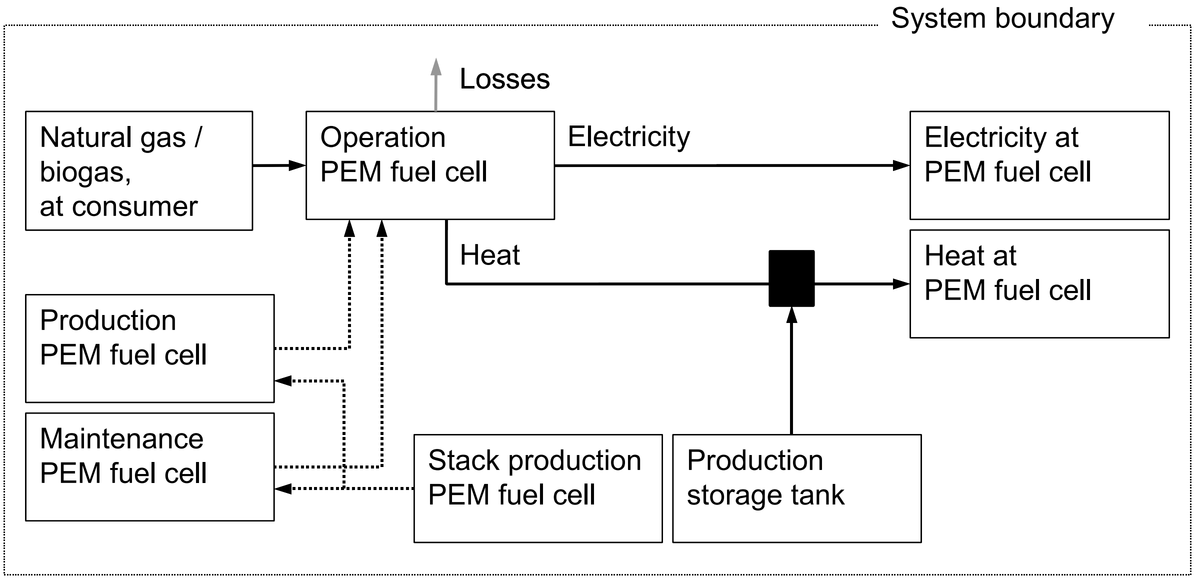

Fig. 5.1 System outline of a 2 kW_{el} PEM fuel-cell system

5.5 Natural gas, burned in PEM fuel cell 2 kW$_{el}$

5.5.1 Technical characteristics

PEM fuel cells are available with an electrical output of between 1 kW$_{el}$ and 250 kW$_{el}$. A PEM fuel cell system with 2 kW$_{el}$ is analysed. For field test units with 4.6 kW$_{el}$, an average electrical efficiency of 23 percent and a total efficiency of 79 percent are measured. An electrical efficiency of 27 to 28 percent is measured for new stacks (without degradation) (Wilk et al., 2005). For small PEM fuel cells, the target values of electrical efficiencies (based on LHV) range between 28 and 35 percent and total efficiencies between >80% and 90 percent (Bine 2004, Fuel Cell Handbook 2004, Dippel 2005, Krewitt et al. 2004). The temperatures from 50 to 70 °C resulting from heat generation allow only applications in newer (low-temperature) heating systems (Fuel Cell Handbook, 2004).

PEM fuel cells have excellent partial-load operating efficiency. The fuel cell stack efficiency improves at lower loads, resulting in an slight increase in the electrical efficiency of the system (Knight et al., 2005). The electrical efficiency remains constant down to 50 percent of the nominal load (Nadal, 1997).

An average electrical efficiency of 32 percent and a total efficiency of 87 percent are assumed for the operation of the 2 kW$_{el}$ PEM fuel-cell system (see Tab. 5.1). The performance values used here are based on target values for serial products and not on values actually achieved in field tests.

Tab. 5.1 Electric and thermal efficiencies and losses of a 2 kW$_{el}$ PEM fuel-cell system

Electricity generation	MJ/MJ$_{in}$	0.32
Heat generation	MJ/MJ$_{in}$	0.55
Total energy output	MJ/MJ$_{in}$	0.87
Heat losses	MJ/MJ$_{in}$	0.13
Waste heat, total *)	MJ/MJ$_{in}$	0.781
*) Based on HHV; natural gas, CH, low pressure: HHV 40.2 MJ/Nm^3; LHV = 36.5 MJ/Nm^3 and including losses as well as heat generated		

5.5.2 Equipment and maintenance needed

The infrastructure needed is defined by the total operating life and the maintenance intervals of the unit. The stack operating life is currently about 4’000 to 8’000 hours (Fuel Cell Handbook 2004, Wilk et al. 2005, DEA 2005). The operating life of the stack is expected to reach 30’000 to 40’000 hours in future systems (DEA 2005, Knight et al. 2005). The maintenance of the fuel cell system (see Section 5.9) includes catalyst replacement, which is needed every three to five years, and stack replacement every four to eight years. The operating life of the auxiliary systems is estimated as 15 years (Krewitt et al. 2004, Pehnt 2002).

An operating life of the auxiliary systems of 15 years or 80’000 operating hours with 14 maintenance sessions during the operating life (maintenance every year) is assumed for the calculations.

The PEM fuel cell system is usually operated in combination with a peak load boiler. Depending on the heat requirement, monovalent operation in small buildings is also possible. For economic reasons, about 3’000 to 5’000 hours of full-load operation per year should be reached, which normally implies a bivalent system design with a peak load boiler. An operating life of 15 years or 5,333 operating hours per year and an average load factor of 67% is assumed, which leads to 3,573 hours of full-load operation per year. The fuel consumption is 6.25 kW at nominal load. Maintenance is needed every 0.086 TJ$_{In}$ of fuel input (five maintenance operations during the life time), and the operating life of the unit is reached after 1.21 TJ$_{In}$ of fuel input.

Besides the infrastructure of the PEM fuel cell system, which also includes the piping for the sanitary equipment and the planning, a storage tank is needed to ensure good system performance. A storage volume of 0.5 m^3 is assumed (0.1 m^3 per kW_{th}). The inventory of the storage tank is based on the 0.65 m^3 storage tank described in Heck (2003). As in Heck (2003), the operating life of the storage tank is 100’000 hours or 1.51 TJ_{In} of fuel input.

This inventory does not include the peak load boiler used in the system design as this depends strongly on the specific application.

The infrastructure processes included are summarised in Tab. 5.2.

Tab. 5.2 Equipment and maintenance of the PEM fuel cell system operated with natural gas

Process	Operating life, interval	Amount
PEM fuel cell 2kWe, future	80’000 h	8.29 E-7 units/MJ_{in}
Maintenance of PEM fuel cell 2kWe, future	14 times per 80’000 h	1.16 E-5 units/MJ_{in}
Storage 650 l , *)	100’000 h	5.84 E-7 units/MJ_{in}
*) For 0.5 m^3 storage size, 0.88 units are used.		

5.5.3 Energy and auxiliaries usage

Natural gas consumption

The system characterisation described in Section 5.4 specifies the use of natural gas from the Swiss low-pressure gas network. According to Faist Emmenegger et al. (2003), this gas has a lower heating value (LHV) of 36.5 MJ/Nm^3 and a higher heating value (HHV) of 40.2 MJ/Nm^3.

Water consumption

Some designs of PEM fuel cell need additional (deionised) water for reforming the natural gas and for stack operation. Other designs include internal water recovery from the waste gas, so that the water consumption is low. The water requirement for operation is neglected.

5.5.4 Emissions to air

Because PEM fuel cell systems do not involve a combustion process like that of reciprocating engines, most of their air emissions are much lower. The major source of emissions is the fuel reforming process, because the heat that it requires is derived from the catalytic combustion of anode-off gas.

The CO_2 emissions for natural gas consumed from the Swiss gas network are 56 g/MJ_{In} (Faist Emmenegger et al. 2003).

Due to the low operating temperatures (about 600°C in the reformer unit), the emissions of nitrogen oxides are very low, at 1 to 4 mg/MJ_{In}.

Carbon monoxide (CO) emissions are low because the catalytic reactions guarantee oxidation of this reformer catalyst toxin. The reported carbon monoxide emissions range between 0.9 and 5.6 mg/MJ_{In}.

The behaviour of hydrocarbon emissions is similar to that of the carbon monoxide emissions. Under normal operating conditions, these emissions are very low (or undetectable). Most sources report only the total hydrocarbon emissions (THC). The reported emissions of unburnt hydrocarbons (excluding explicitly stated methane emissions) range between 0.12 and 0.4 mg/MJ_{In}. An average emission level of 0.3 mg/MJ_{In} NMVOC is used here.

Only two sources state separate methane emissions (Pehnt 2002, Fleischer & Oertel 2003). The emission value of 8.3 mg/MJ_{In} is very high and seems to include a non-optimised reforming process. An average emission level of 4 mg/MJ_{In} methane is used here.

The reported particulate emissions are zero or very low (0.5 µg/MJ_{In}). A particulate emission level of 0.2 µg/MJ_{In} is used here. It is assumed that these emissions are emitted as PM2.5 particles.

No N_2O emissions are reported in the available sources (Pehnt 2002, Krewit et al. 2004). These emissions are therefore neglected.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. Because sulphur is toxic to the catalysts used here, it is removed by a catalytic reaction before entering the fuel processing unit. The SO_2 emissions therefore do not occur during operation but when the catalyst is regenerated. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied here.

The emission values used for operation with natural gas are summarised in Tab. 5.3.

Tab. 5.3 Emissions to air of PEM fuel cell systems operated with natural gas

NOx mg/MJ_{In}	CO mg/MJ_{In}	THC mg/MJ_{In}	Particulates mg/MJ_{In}	SO_2 mg/MJ_{In}	Source
2.25	2.67	0.4	-	-	Knight et al. (2005)
0.9	1.7	0.3 *)	0	0	Krewitt et al. (2004)
0.9	1.7	8.6 **)	0	0	Pehnt (2002)
3.8	2.6	0.4	-	-	Goldstein et al. (2003)
1.2	2.7	8.6 ***)	-	-	Fleischer & Oertel (2003)
1.18	0.59	0.12	0	0	Probas (2000)
<2	-	-	-	-	Jansen et al. (2000)
0.25-2.2	0.003-5.6	-	< 0.0005	< 0.005	Nadal (1997)
1.3	**1.7**	**4.3 ****)**	**0.0002**	**0.55**	**Used in this inventory**

*) No additional methane emission. Otherwise identical values to those in Pehnt (2002),
**) Additional 8.3 mg/MJ_{In} methane emission, included in THC value (0.3 mg/MJ_{In} NMVOC)
***) Additional 8.3 mg/MJ_{In} methane emission, included in THC value (0.3 mg/MJ_{In} NMVOC)
****) Of this, 4 mg/MJ_{In} as CH4 and 0.3 mg/MJ_{In} as NMVOC

5.5.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, natural gas, allocation exergy, at PEM fuel cell 2 kWe, future
- electricity, natural gas, allocation exergy, at PEM fuel cell 2 kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is applied in this project. An allocation based on exergy leads to higher specific requirements and emissions per kWh of electricity compared to 1 kWh of heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 5.4.

Tab. 5.4 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	32 %	55 %	87 %
Exergy factor *)	1.000	0.093	-
Allocation factor	86.3 %	13.7 %	100.0 %
*) Based on a hot water temperature of 60/40 °C and an ambient temperature of 20 °C for heat production			

5.5.6 Data quality considerations

Tab. 5.5 shows the multi-output process raw data and data-quality indicators of the inventory of natural gas, burned in PEM fuel cell 2 kW_{el}, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached within the next 5 years.

Tab. 5.5 Multi-output process raw data of natural gas, burned in PEM fuel cell 2 kW$_{el}$, future

	Name	Location	InfrastructureProcess	Unit	natural gas, burned in PEM fuel cell 2kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, natural gas, allocation exergy, at PEM fuel cell 2kWe, future	electricity, natural gas, allocation exergy, at PEM fuel cell 2kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, natural gas, allocation exergy, at PEM fuel cell 2kWe, future	CH	0	MJ	5.50E-1				100	0
	electricity, natural gas, allocation exergy, at PEM fuel cell 2kWe, future	CH	0	kWh	8.89E-2				0	100
technosphere	PEM fuel cell 2kWe, future	CH	1	unit	8.29E-7	1	1.14	(2,3,2,1,1,4); uncertainty of life time	13.7	86.3
	maintenance PEM fuel cell 2kWe	CH	0	unit	1.16E-5	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	13.7	86.3
	storage 650 l Mini-BHKW	CH	1	unit	5.84E-7	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	natural gas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	13.7	86.3
emission air, high population density	Carbon dioxide, fossil	-	-	kg	5.60E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	13.7	86.3
	Carbon monoxide, fossil	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on different references	13.7	86.3
	Methane, fossil	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on few references	13.7	86.3
	Nitrogen oxides	-	-	kg	1.30E-6	1	1.53	(2,3,2,1,1,4); estimate based on different references	13.7	86.3
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	3.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on different references	13.7	86.3
	Particulates, < 2.5 um	-	-	kg	2.00E-10	1	3.16	(4,4,3,2,3,5); estimate based on one references	13.7	86.3
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	13.7	86.3
	Heat, waste	-	-	MJ	7.81E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	13.7	86.3

5.6 Biogas gas, burned in PEM fuel cell 2 kW_{el}

5.6.1 Technical characteristics

The operation of PEM fuel cells with low-calorific gases such as landfill gas and digester gas is difficult due to the high requirements made on the gas purity of the fuel cell stack. PEM fuel-cell systems operated with raw biogas drawn directly from the production site (e.g. agricultural site or waste water plant) are not considered in this inventory.

Only biogas distributed in the regular natural gas network is considered. This biogas has a quality similar to natural gas. Its methane content must be at least 96 vol-%.

Under these conditions, the operation of the PEM fuel cell with biogas is similar to that with natural gas (see Section 2.5.1). For operation of the PEM fuel cell with refined biogas, an average electrical efficiency of 32 percent and a total efficiency of 87 percent is assumed (see Tab. 5.6).

Tab. 5.6 Electric and thermal efficiencies and losses of a 2 kW_{el} PEM fuel-cell system

Electricity generation	MJ/MJ_{in}	0.32
Heat generation	MJ/MJ_{in}	0.55
Total energy output	MJ/MJ_{in}	0.87
Heat losses	MJ/MJ_{in}	0.13
Waste heat, total *)	MJ/MJ_{in}	0.787
*) Based on HHV; biogas, CH, high pressure: HHV 38.146 MJ/Nm^3; LHV = 34.450 MJ/Nm^3		

5.6.2 Equipment and maintenance needed

The infrastructure needed is identical to that of an engine operated with natural gas presented in Section 5.5.2 (operated with natural gas).

An operating life of 80’000 hours or 15 years with fourteen maintenance sessions during the operating life is assumed. Maintenance is needed every 0.086 TJ_{In} of fuel input and the operating life of the unit is reached after 1.21 TJ_{In} of fuel input. As for the unit operated with natural gas, a storage tank volume of 0.5 m^3 is assumed, which has to be replaced after every 1.51 TJ_{In} of fuel input.

5.6.3 Energy and auxiliaries usage

Biogas consumption

The distribution requirements (energy, leakages) are similar to those of natural gas. Only the composition of the emissions differs due to the different compositions of biogas and natural gas. The dataset “methane, 96 vol-%, from biogas, low pressure, at consumer” is used as the process input for the PEM fuel cell. According to Jungbluth et al. (2007), the gas has a lower heating value of 34.45 MJ/Nm^3 and a higher heating value of 38.15 MJ/Nm^3. On the basis of the lower heating value, 0.029 Nm^3/MJ_{In} of biogas are required.

Water consumption

As for operation with natural gas, no water consumption is included.

5.6.4 Emissions to air

The biogenic CO_2 emissions are calculated on the basis of the carbon content of the biogas mix. The values presented in Tab. 5.7 also take into account carbon emitted in the form of CO, CH_4 and NMVOC. For operation of the PEM fuel cell system with refined biogas, identical emission factors are used to those for operation with natural gas (see Section 5.5.4).

According to the biogas composition presented in Jungbluth et al. (2007), the refined biogas has a slightly lower nitrogen content than natural gas. Due to the low NO_X emissions of PEM fuel cells, this difference is neglected and identical emission factors are used. An NO_X emission factor of 1.3 mg NO_X/MJ_{In} is applied for this inventory.

Carbon monoxide (CO) emissions are low because the catalytic reactions guarantee the oxidation of this reformer catalyst toxin. As for operation with natural gas, an emission factor of 1.7 mg CO/MJ_{In} is applied here.

The behaviour of hydrocarbon emissions is similar to that of the carbon monoxide emissions. Under normal operating conditions, these emissions are very low (or undetectable). Most sources report only the total hydrocarbon emissions (THC). The reported emissions of unburnt hydrocarbons range between 0.12 and 0.4 mg/MJ_{In}. An average emission level of 0.3 mg/MJ_{In} NMVOC is used here.

Only two sources state separate methane emissions (Pehnt 2002, Fleischer & Oertel 2003). The emission value of 8.3 mg/MJ_{In} is very high and seems to include a non-optimised reforming process. An average emission level of 4 mg/MJ_{In} methane is used here.

The reported particulate emissions are zero or very low (0.5 $\mu g/MJ_{In}$). A particulate emission level of 0.2 $\mu g/MJ_{In}$ is used here. It is assumed that these emissions are emitted as PM2.5 particles.

No N_2O emissions are reported in the available sources (Pehnt 2002, Krewit et al. 2004). These emissions are therefore neglected.

The SO_2 emissions are derived from the sulphur content (odoration) of the natural gas used. The H_2S content in odorated natural gas is similar to that of the biogas presented in Jungbluth (2007). Because sulphur is toxic to the catalysts used, it is removed by a catalytic reaction before entering the fuel processing unit. The SO_2 emissions therefore do not occur during operation but when the catalyst is regenerated. In accordance with Heck (2003) and Faist Emmenegger et al. (2003), an SO_2 emission factor of 0.55 mg SO_2/MJ_{In} is applied here.

Tab. 5.7 CO_2 emissions and carbon balance

	Emission factor	Carbon content	Share
Biogas input	-	524,992.3 mg C / Nm^3 15,239.3 mg C / MJ_{In}	100.00 %
Carbon dioxide, biogenic	55,824.2 mg/MJ_{In}	15,235.4 mg C / MJ_{In}	99.97 %
Carbon monoxide, biogenic	1.7 mg/MJ_{In}	0.7 mg C / MJ_{In}	0.01 %
Methane, biogenic	4 mg/MJ_{In}	3.0 mg C / MJ_{In}	0.02 %
NMVOC *)	0.3 mg/MJ_{In}	0.2 mg C / MJ_{In}	0.00 %
*) Carbon content calculated as C5H12 (Pentane)			

5.6.5 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, biogas, allocation exergy, at PEM fuel cell 2 kWe, future
- electricity, biogas, allocation exergy, at PEM fuel cell 2 kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is used in this project. Allocations based on exergy lead to higher specific requirements and emissions per kWh of electricity compared to 1 kWh heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 5.8.

Tab. 5.8 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	32 %	55 %	87 %
Exergy factor *)	1.000	0.093	-
Allocation factor	86.3 %	13.7 %	100.0 %
*) Based on a hot water temperature of 60/40 °C and an ambient temperature of 20 °C for heat production			

5.6.6 Data quality considerations

Tab. 5.9 shows the multi-output process raw data and data-quality indicators of the inventory of biogas, burned in PEM fuel cell 2 kW_{el}, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached within the next 5 years.

Tab. 5.9 Multi-output process raw data of biogas, burned in PEM fuel cell 2 kW$_{el}$, future

	Name	Location	InfrastructureProcess	Unit	biogas, burned in PEM fuel cell 2kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment	heat, biogas, allocation exergy, at PEM fuel cell 2kWe, future	electricity, biogas, allocation exergy, at PEM fuel cell 2kWe, future
	Location InfrastructureProcess Unit				CH 0 MJ				CH 0 MJ	CH 0 kWh
allocated	heat, biogas, allocation exergy, at PEM fuel cell 2kWe, future	CH	0	MJ	5.50E-1				100	0
	electricity, biogas, allocation exergy, at PEM fuel cell 2kWe, future	CH	0	kWh	8.89E-2				0	100
technosphere	PEM fuel cell 2kWe, future	CH	1	unit	8.29E-7	1	1.14	(2,3,2,1,1,4); uncertainty of life time	13.7	86.3
	maintenance PEM fuel cell 2kWe	CH	0	unit	1.16E-5	1	1.14	(2,3,2,1,1,4); uncertainty of maintenance cycle	13.7	86.3
	storage 650 l Mini-BHKW	CH	1	unit	5.84E-7	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	1.00E+0	1	1.05	(nA,nA,nA,nA,nA,nA); input	13.7	86.3
emission air, high population density	Carbon dioxide, biogenic	-	-	kg	5.58E-2	1	1.07	(2,nA,nA,nA,1,nA); composition of biogas	13.7	86.3
	Carbon monoxide, biogenic	-	-	kg	1.70E-6	1	5.02	(2,3,2,1,1,4); estimate based on different references	13.7	86.3
	Methane, biogenic	-	-	kg	4.00E-6	1	1.62	(4,3,2,1,1,5); estimate based on few references	13.7	86.3
	Nitrogen oxides	-	-	kg	1.30E-6	1	1.53	(2,3,2,1,1,4); estimate based on different references	13.7	86.3
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	3.00E-7	1	1.58	(4,3,2,1,1,4); estimate based on different references	13.7	86.3
	Particulates, < 2.5 um	-	-	kg	2.00E-10	1	3.16	(4,4,3,2,3,5); estimate based on one references	13.7	86.3
	Sulfur dioxide	-	-	kg	5.50E-7	1	1.07	(2,nA,nA,nA,1,nA); composition of natural gas	13.7	86.3
	Heat, waste	-	-	MJ	7.87E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	13.7	86.3

5.7 Manufacture of a 2 kW_{el} PEM fuel cell

5.7.1 Technical characteristics

The infrastructure dataset of the 2 kW_{el} PEM fuel-cell unit includes the most important materials used for its production, the transport of these materials and the energy needed for its production and engineering. The production process involves various steps including raw material cutting, casting, machining and welding. Steel is the principal material used, others being stainless steel (reformer unit) and special materials for the stack production (platinum, PTFE). The total weight of the analysed unit is 120 kg.

5.7.2 Manufacturing site

No data are available on the production infrastructure for PEM fuel cell units. The infrastructure size is approximated with a production facility for similar products (Viessmann 2005). This production site includes 35,300 m^2 of floor space (offices, production and storage). An output of 85’000 units per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17,700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105,900 m^3. The service life of the buildings is assumed to be 50 years. Each unit bears the environmental burdens of 0.0042 m^2 of the building hall and 0.025 m^3 of the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with the data of a similar production site (Viessmann 2005). On this site, 63,500 m^2 is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of 0.015 m^2 of land transformation and 0.75 m^2 a of land occupation.

5.7.3 Raw materials, energy and auxiliaries

The amount of raw materials used for the production of the 2 kW_{el} PEM fuel-cell stack is derived from Krewitt et al. (2004). Only the material for the PEM fuels cell unit is included in this data and neither the energy requirement for the production process nor transport requirements are considered.

No detailed data on the inverter are available in Krewitt et al. (2004). Only the weight of the unit of 0.25 kg per kW_{el} is given. This specific weight is too low for a small inverter of 2 kW_{el}, so that the inverter described in Jungbluth & Tuchschmid (2007) is used. Due to the larger size (2.5 kW_{el}) of this unit, only 80% of this amount is used.

For each PEM fuel cell unit (2 kWel), an additional energy requirement of 458 MJ for heat (natural gas, at industrial furnace >100 kW) and 64 kWh of electricity (medium voltage, production UCTE, at grid) is included for heating and electricity on the production site. The amount used is based on the specific energy requirement per kg product of a similar production site (Viessmann 2005).

No data are available on the water consumption for manufacturing PEM fuel cell units. The amount used (see Tab. 5.10) is based on the specific water requirement of 1.22 litre per kg of product of a similar production site (Viessmann 2005).

For the transportation of the raw materials, the standard distances for Europe according to (Frischknecht et al., 2004) are applied. For metals and plastics, 200 km for rail transport and 100 km for road transport (lorry >16t, fleet average) are used here. These distances are also applied to the fuel cell stack because it is not manufactured at the same location as the total unit. For the installation of the unit, a distance of 200 km by road transport is assumed (lorry >16t, fleet average).

Additional material and energy is needed for the auxiliary installations (e.g. sanitary ducting). These parts are modelled with the dataset “heating, sanitary equipment Mini-BHKW” described in Heck

(2003). In view of the larger size of the CHP unit described in Heck (2003), only 60% of this amount is used.

Additional energy is consumed for planning and engineering. Experience from similar projects suggests that 20 working hours of planning and engineering are needed for the 2 kW_{el} unit. On the basis of data from Aebischer and Catenazzi (2006), a specific energy consumption of 15 MJ/h of heat (light fuel oil burned in a 100 kW non-modulating boiler) and 2 kWh/h of electricity (low voltage, at grid, CH) is used to calculate the energy requirement.

Heck (2003) specifies a transport distance of 250 pkm for planning and engineering a 5 kW_{el} co-generation unit. A longer transport distance is used for planning and engineering the fuel cells because only a few fuel-cell specialists in Switzerland are prepared to plan such units and more than one site visit will be necessary. It is assumed that the construction site is visited twice and the distance of 200 km (return trip) for each visit is covered by car.

The material and energy data presented in Krewitt et al. (2004) are scaled up (linearly) to a 2 kW_{el} PEM fuel-cell system. The data are shown in Tab. 5.10

Tab. 5.10 Raw materials, energy and auxiliaries of the manufacture of a 2 kW_{el} PEM fuel-cell system

Size of the PEM fuel cell unit (nominal electrical power)	Unit -	Used in this study 2 kW_{el}	Remarks	
Steel, low-alloyed, at plant	kg	39.4		R
Chromium steel 18/8, at plant	kg	46.2	1)	R
Aluminium, production mix, wrought alloy, at plant	kg	4.6		R
Cast iron, at plant	kg	1.6		R
Titanium dioxide, production mix, at plant	kg	0.14		R
Charcoal, at plant	kg	0.5	2)	R
Polyethylene, HDPE, granulate, at plant	kg	4.8		I
Polypropylene, granulate, at plant	kg	0.5		I
Polystyrene foam slab, at plant	kg	0.6		I
Platinum, at regional storage	kg	0.0012		R
Sheet rolling, steel	kg	39.4	3)	
Sheet rolling, chromium steel	kg	46.2	3)	
Sheet rolling, aluminium	kg	4.6	3)	
Injection moulding	kg	5.3	3)	
Stack PEM fuel cell 2kWe, future	unit	1		
Inverter, 2500W, at plant	unit	0.8		
Heating, sanitary equipment Mini-BHKW (5 kWel)	unit	0.65		
Water for manufacturing (unspecified natural origin)	m3	0.146	5)	W
Transport, freight, rail, RER	tkm	24	4)	
Transport, lorry >16t, fleet average, RER	tkm	36	4)	
Heating production site: natural gas, at industrial furnace >100kW	MJ	458	5)	
Electricity production site: medium voltage, production UCTE, at grid	kWh	64	5)	
Heating engineering services: light fuel oil, burned in boiler 100kW, non-modulating	MJ	300		
Electricity engineering services: low voltage, at grid, at grid, CH	kWh	40		
Transport engineering: transport, passenger car, CH	pkm	400		
Dismantling: R = Recycling; I = Disposal in municipal incineration plant; W = Disposal in wastewater plant 1) According to Krewitt et al. (2004) high-alloyed steel 2) Proxy process for activated carbon 3) For pre-fabrication of raw material used 4) Standard distances for Europe used for raw materials 5) Approximation with data from Viessmann (2005)				Dismantling

5.7.4 Emissions to air and water

Emissions to air are included in the processes unit used (e.g. heating or transport processes). No further process-related air emissions occur. An average wastewater treatment process is used for the wastewater disposal due to a lack of data on water emissions from manufacturing. It is assumed that all the fresh water used is disposed of as wastewater via a suitable treatment plant.

5.7.5 Dismantling

After their service life, PEM fuel cells will be dismantled and the materials recycled or disposed of. It is assumed that all metals and catalyst material (especially platinum) will be recycled. No environmental burdens from dismantling and recycling are included for these materials (cut-off). Final disposal of the plastic materials in a municipal incineration plant is assumed. The amount and type of disposal of the different materials is indicated in Tab. 5.10.

5.7.6 Data quality considerations

Tab. 5.11 shows the unit process raw data and data-quality indicators of the manufacture of a PEM fuel cell unit with 2 kW_{el} of nominal electrical power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources and an estimate for different additional processes not covered in the data source. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 5.11 Unit process raw data of the manufacture of a 2 kW$_{el}$ PEM fuel-cell system

	Name	Location	InfrastructureProces	Unit	PEM fuel cell 2kWe, future	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	PEM fuel cell 2kWe, future	CH	1	unit	1			
technosphere	steel, low-alloyed, at plant	RER	0	kg	3.94E+1	1	1.35	(2,4,3,2,3,5); value for expected serial production
	chromium steel 18/8, at plant	RER	0	kg	4.62E+1	1	1.35	(2,4,3,2,3,5); value for expected serial production
	aluminium, production mix, wrought alloy, at plant	RER	0	kg	4.60E+0	1	1.33	(2,4,2,2,3,5); value for expected serial production
	cast iron, at plant	RER	0	kg	1.60E+0	1	1.33	(2,4,2,2,3,5); value for expected serial production
	titanium dioxide, production mix, at plant	RER	0	kg	1.40E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
	charcoal, at plant	GLO	0	kg	5.00E-1	1	2.11	(4,4,2,2,5,5); proxy for activated carbon
	polyethylene, HDPE, granulate, at plant	RER	0	kg	4.80E+0	1	1.33	(2,4,2,2,3,5); value for expected serial production
	polypropylene, granulate, at plant	RER	0	kg	5.00E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
	polystyrene foam slab, at plant	RER	0	kg	6.00E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
	platinum, at regional storage	RER	0	kg	1.20E-3	1	1.35	(3,4,2,2,3,5); value for expected serial production
	inverter, 2500W, at plant	RER	1	unit	8.00E-1	1	3.15	(4,4,2,2,3,5); data from 3kWel unit for use in photovoltaics
	stack PEM fuel cell 2kWe, future	CH	1	unit	1.00E+0	1	3.00	(nA.,nA.,nA.,nA.,1,nA.); material
	heating, sanitary equipment Mini-BHKW	CH	1	unit	6.50E-1	1	3.16	(4,4,2,5,3,5); approximation based on similar process
	sheet rolling, steel	RER	0	kg	3.94E+1	1	1.25	(2,4,2,2,1,5); based on material input
	sheet rolling, chromium steel	RER	0	kg	4.62E+1	1	1.25	(2,4,2,2,1,5); based on material input
	sheet rolling, aluminium	RER	0	kg	4.60E+0	1	1.25	(2,4,2,2,1,5); based on material input
	injection moulding	RER	0	kg	5.30E+0	1	1.25	(2,4,2,2,1,5); based on material input
	transport, freight, rail	RER	0	tkm	2.40E+1	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	3.60E+1	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, passenger car	CH	0	pkm	4.00E+2	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	4.58E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	3.00E+2	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	6.40E+1	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	electricity, low voltage, at grid	CH	0	kWh	4.00E+1	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	5.30E+0	1	1.33	(2,4,2,2,3,5); disposal of plastic parts
	disposal, building, polystyrene isolation, flame-retardant, to final disposal	CH	0	kg	6.00E-1	1	1.33	(2,4,2,2,3,5); disposal of plastic insulating material
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	1.46E-1	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	2.50E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
	building, hall, steel construction	CH	1	m2	4.20E-3	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
resource, in water	Water, unspecified natural origin	-	-	m3	1.46E-1	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	7.50E-1	1	1.65	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, from unknown	-	-	m2	1.50E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, to industrial area, built up	-	-	m2	1.50E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
emission air, high population density	Heat, waste	-	-	MJ	3.74E+2	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

5.8 Manufacture of Stack PEM fuel cell 2 kW_{el}

5.8.1 Technical characteristics

The infrastructure dataset of the 2 kW_{el} PEM fuel-cell stack includes the most important materials used for its production, the transport of these materials and the energy needed for its production. The production process involves various steps including raw material cutting, screen printing, drying and injection moulding. Graphite, aluminium, stainless steel, PTFE and platinum are the materials used. The total weight of the analysed stack is 12.3 kg.

5.8.2 Manufacturing site

No data are available on the infrastructure for PEM fuel-cell stack production. The infrastructure size is approximated with a production facility for conventional heating systems (Viessmann 2005). This production site includes 35,300 m^2 of floor space (offices, production and storage). An output of 800'000 stacks per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17,700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105,900 m^3. The service life of the buildings is assumed to be 50 years. Each unit bears the environmental burdens of $0.44*10^{-3}$ m^2 for the building hall and $2.6*10^{-3}$ m^3 for the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with the data of a similar production site (Viessmann 2005). On this site, 63,500 m^2 is sealed. This area is accounted as "industrial area, built up" (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of $1.6*10^{-3}$ m^2 land transformation and $79*10^{-3}$ m^2 a of land occupation.

5.8.3 Raw materials, energy and auxiliaries

The amount of raw materials used for the production of the 2 kW_{el} PEM fuel-cell unit is derived from Krewitt et al. (2004). The material for the stack and the electricity needed for production are included in this data.

An additional energy requirement of 47 MJ for heating (natural gas, at industrial furnace >100kW) is included for each stack (2 kWel). This amount is based on the specific energy requirement of 3.8 MJ per kg of product for a similar production site (Viessmann 2005).

For the transportation of the raw materials, the standard distances for Europe according to (Frischknecht et al., 2004) are applied: 200 km for rail transport and 100 km for road transport (lorry >16t, fleet average) are used for metals and plastics.

The amount of material used for the bipolar plates given in Krewitt et al. (2004) is rather high for future production processes, namely 4.5 kg of graphite and 1.1 kg of polyvinylidenfluoride per kW_{el}. According to Ruge (2003), optimised bipolar plates have a weight of about 1.9 kg per kW_{el}. If injection moulding is used for the production of the bipolar plates, polyvinylidenfluoride is unsuitable (SGL Carbon 2004). In order to support injection moulding, phenolic resins or polypropylene are used instead. The amounts of material as presented in Krewitt et al. (2004) are used here. A phenolic resin is used instead of polyvinylidenfluoride as the plastic base material for the bipolar plate.

According to Krewitt et al. (2004), the amount of catalyst needed for future production is 0.75 g per kW_{el}. The amount used in actual field test units is around 2-3 g per kW_{el}. The amounts of material as presented in Krewitt et al. (2004) are used here.

The material and energy data presented in Krewitt et al. (2004) are scaled up (linearly) to a 2 kW_{el} PEM fuel-cell stack. The data used is shown in Tab. 5.12.

Tab. 5.12 Raw materials, energy and auxiliaries of the manufacture of a 2 kW_{el} PEM fuel-cell stack

Size of the PEM fuel-cell unit (nominal electrical power)	Unit -	Used in this study 2 kW_{el}	Remarks	
Chromium steel 18/8, at plant	kg	0.2	1)	R
Aluminium, production mix, wrought alloy, at plant	kg	0.6		R
Graphite, at plant	kg	9	2)	I
Phenolic resin, at plant	kg	2.2	2)	I
Glass fibre, at plant	kg	0.2	3)	I
Carbon black, at plant	kg	0.0016		I
Tetrafluoroethylene, at plant	kg	0.104		I
Platinum, at regional storage	kg	0.0015	4)	R
Isopropanol, at plant	kg	0.019	5)	E
Water, deionised, at plant	kg	0.012	5)	
Transport, freight, rail, RER	tkm	2.5	6)	
Transport, lorry >16t, fleet average, RER	tkm	1.2	6)	
Heating production site: natural gas, at industrial furnace >100kW	MJ	47	7)	
Electricity, medium voltage, production UCTE, at grid	kWh	33.8		
Dismantling: R = Recycling; I = Disposal in municipal incineration plant; E = Direct emission 1) According to Krewitt et al. (2004) high-alloyed steel 2) Phenolic resin is used for production with injection moulding (SGL Carbon, 2004) instead of polyvinylidenfluoride as described in Krewitt et al (2004). The value may be lower for a future production process. 3) Proxy process for carbon fibre 4) All catalyst material accounted as platinum 5) Amount based on a 250 kW_{el} PEM fuel cell stack presented in Karakoussis et al. (2000) 6) Standard distances for Europe used 7) Approximation with data from Viessmann (2005)				Dismantling

5.8.4 Emissions to air

Most emissions to air are included in the unit processes used (e.g. heating or transport processes). The air emissions from the solvent used (propanol) in the production process are included. It is assumed that 100% of the used solvent (0.019 kg) is emitted to air.

5.8.5 Dismantling

After their service life, the PEM fuel-cell stacks are dismantled and the materials recycled or disposed of. It is assumed that all metals and the catalyst material (especially platinum) will be recycled. No environmental burdens from dismantling and recycling are included (cut-off) for these materials. Final disposal of the plastic materials in a municipal incineration plant is assumed. The amount and type of disposal of the different stack materials is indicated in Tab. 5.12. Depending on the waste treatment process additional water content of the waste is added to the weight of the disposed material (e.g. for plastic material). The value used in Tab. 5.13 includes the water content of the waste.

5.8.6 Data quality considerations

Tab. 5.13 hows the unit process raw data and data-quality indicators of the manufacture of a PEM fuel cell stack with 2 kW_{el} of nominal electrical power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for various additional processes not covered in the data source. Some data of the material used are uncertain due to still unknown future developments for the serial production of PEM fuel-cell stacks. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 5.13 Unit process raw data of the manufacture of a 2 kW_{el} PEM fuel-cell stack

	401	InputGroup	OutputGroup	Name	Location	InfrastructureProce	Unit	stack PEM fuel cell 2kWe, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	662			Location				CH			
	493			InfrastructureProcess				1			
	403			Unit				unit			
product		-	0	stack PEM fuel cell 2kWe, future	CH	1	unit	1			
technosphere		5	-	chromium steel 18/8, at plant	RER	0	kg	2.00E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
		5	-	aluminium, production mix, wrought alloy, at plant	RER	0	kg	6.00E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
		5	-	graphite, at plant	RER	0	kg	9.00E+0	1	1.35	(3,4,2,2,3,5); high value for a future serial production
		5	-	phenolic resin, at plant	RER	0	kg	2.20E+0	1	1.35	(3,4,2,2,3,5); high value for a future serial production
		5	-	glass fibre, at plant	RER	0	kg	2.00E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
		5	-	carbon black, at plant	GLO	0	kg	1.60E-3	1	2.11	(4,4,2,2,5,5); proxy for activated carbon
		5	-	tetrafluoroethylene, at plant	RER	0	kg	1.04E-1	1	1.33	(2,4,2,2,3,5); value for expected serial production
		5	-	platinum, at regional storage	RER	0	kg	1.50E-3	1	1.33	(2,4,2,2,3,5); value for expected serial production
		5	-	isopropanol, at plant	RER	0	kg	1.90E-2	1	1.35	(3,4,2,2,3,5); approximation based on similar process
		5	-	water, deionised, at plant	CH	0	kg	1.20E-2	1	1.35	(3,4,2,2,3,5); data from 3kWel unit for use in photovoltaics
		5	-	transport, freight, rail	RER	0	tkm	2.50E+0	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
		5	-	transport, lorry >16t, fleet average	RER	0	tkm	1.20E+0	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
		5	-	natural gas, burned in industrial furnace >100kW	RER	0	MJ	4.70E+1	1	1.33	(2,4,1,2,3,5); approximation with company data of similar branch
		5	-	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	3.38E+1	1	1.33	(2,4,1,2,3,5); approximation with company data of similar branch
		5	-	disposal, plastic, industr. electronics, 15.3% water, to municipal incineration	CH	0	kg	1.32E+1	1	1.64	(4,4,2,2,4,5); proxy for disposal of moulded bipolar plates
		5	-	disposal, polyvinylfluoride, 0.2% water, to municipal incineration	CH	0	kg	1.04E-1	1	1.33	(2,4,2,2,3,5); disposal of membrane material
		5	-	building, multi-storey	RER	1	m3	2.60E-3	1	3.34	(4,4,2,5,4,5); rough estimation based on company data of similar branch
		5	-	building, hall, steel construction	CH	1	m2	4.40E-4	1	3.34	(4,4,2,5,4,5); rough estimation based on company data of similar branch
resource, land		4	-	Occupation, industrial area	-	-	m2a	7.90E-2	1	1.90	(4,4,2,5,4,5); rough estimation based on company data of similar branch
		4	-	Transformation, from unknown	-	-	m2	1.60E-3	1	2.35	(4,4,2,5,4,5); rough estimation based on company data of similar branch
		4	-	Transformation, to industrial area, built up	-	-	m2	1.60E-3	1	2.35	(4,4,2,5,4,5); rough estimation based on company data of similar branch
emission air, high population density		-	4	Propanol	-	-	kg	1.90E-2	1	1.69	(4,4,2,2,3,5); estimation based on material input
		-	4	Heat, waste	-	-	MJ	1.22E+2	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

5.9 Maintenance of the 2 kW_{el} PEM fuel cell

5.9.1 Technical characteristics

The dataset representing the maintenance of the PEM fuel-cell system includes the estimated material use and transport services for these activities.

PEM fuel cells have the potential for low maintenance costs because they have few moving parts. Routine maintenance mainly includes ancillary systems such as fuel filters, reformer igniters, water treatment beds, sulphur absorbent bed catalysts as well as the pumps and fans needed for operating the fuel cell system. The filter should be replaced periodically every 2’000 to 4’000 hours (Knight et al., 2005). Major overhaul of the fuel cell system involves the replacement of catalysts and of the stack. Catalyst replacement is needed every three to five years and the stack is expected to have a service life of between four and eight years (Knight et al., 2005).

5.9.2 Raw materials, energy and auxiliaries

It is assumed that maintenance will be carried out once a year (equals 3,573 hours of full-load operation). During the annual maintenance, only minor replacement operations are carried out (e.g. filter replacement). The amount of this additional material is estimated to be 1% of the total plant weight (= 1.2 kg). It is assumed to be mainly stainless steel. In addition, the catalysts (platinum, titanium dioxide and charcoal) are replaced every fourth year and the stack is replaced every sixth year during maintenance. So 25% of the catalysts and 17% of the stack are replaced on average in each maintenance operation. It is assumed that the service personnel travel 200 km for each service.

5.9.3 Emissions to air

Emissions to air are included in the unit processes used (e.g. transport processes). No further process-related air emissions occur.

5.9.4 Dismantling

It is assumed that all metals (1.2 kg) and catalyst material (0.16 kg) will be recycled. For those materials, no burdens from dismantling and recycling are included (cut-off). The dismantling of the stack is already included in the process “stack PEM fuel cell 2kWe, future”.

5.9.5 Data quality considerations

Tab. 5.14 shows the unit process raw data and data-quality indicators of the maintenance of a PEM fuel-cell system with 2 kW_{el} of nominal electrical power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. The inventory is based on only a rough estimate for the process. Large uncertainties exist for the transport distances and the amount of material used. In general, therefore, the data quality is not very reliable.

Tab. 5.14 Unit process raw data of the maintenance of a 2 kW_{el} PEM fuel-cell system

	Name	Location	InfrastructureProce	Unit	maintenance PEM fuel cell 2kWe	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				unit			
product	maintenance PEM fuel cell 2kWe	CH	0	unit	1			
technosphere	chromium steel 18/8, at plant	RER	0	kg	1.20E+0	1	1.38	(4,5,n.A.,n.A.,1,5); estimate
	titanium dioxide, production mix, at plant	RER	0	kg	3.50E-2	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected lifetime of reformer catalyst
	charcoal, at plant	GLO	0	kg	1.25E-1	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected lifetime of desulfuring unit
	platinum, at regional storage	RER	0	kg	3.75E-4	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected lifetime of reformer catalyst
	stack PEM fuel cell 2kWe, future	CH	1	unit	1.67E-1	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expected stack lifetime in future
	transport, passenger car	CH	0	pkm	2.00E+2	1	2.14	(4,5,n.A.,n.A.,1,5); estimated

5.10 Cumulative results and interpretation

5.10.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Multi-output process “natural gas, burned in PEM fuel cell 2 kW$_{el}$, future”

The major part of the NMVOC (92%), nitrogen oxide (76%) and particulate < 2.5um emissions (34%) and the cumulative energy demand (fossil: 96%, nuclear: 18%) are caused by the natural gas used for operation. The major part of the carbon dioxide (83%) emissions are caused by direct emissions from operation. Also a small part of the nitrogen oxide (4%) emissions are caused by direct emissions. The manufacture of the fuel cell is for the nitrogen oxide (9%) and particulate < 2.5um emissions (37%) and the cumulative energy demand (fossil: 2%, nuclear: 47%) of importance. Tab. 5.15 shows selected LCI results and cumulative energy demands for electricity and heat production with a PEM fuel cell system. The results depend significantly on the chosen allocation method.

Multi-output process “biogas, burned in PEM fuel cell 2 kW$_{el}$, future”

The major part of the fossil carbon dioxide (81%), NMVOC (65%), nitrogen oxide (62%) and particulate < 2.5um emissions (41%) and the cumulative energy demand (biomass: 70%, fossil: 82%, nuclear: 94%) are caused by the refined biogas used for operation. A small part of the nitrogen oxide (6%) emissions are caused by direct emissions from operation. The manufacture of the fuel cell is for the fossil carbon dioxide (10%), NMVOC (13%), nitrogen oxide (15%) and particulate < 2.5um emissions (33%) and the cumulative energy demand (fossil: 3%, nuclear: 9%) of importance. Tab. 5.15 shows selected LCI results and cumulative energy demands for electricity and heat production with a PEM fuel cell system. The results depend significantly on the chosen allocation method.

Process “PEM fuel cell 2 kW$_{el}$, future ”

The major part of the emissions and cumulative energy demand are caused by the material and energy used for the production of the auxiliary systems of the fuel cell. The fuel cell stack is only for a minor part of the fossil carbon dioxide (5%), NMVOC (6%), nitrogen oxide (4%) and particulate < 2.5um emissions (3%) responsible. Also for the cumulative energy demand (fossil: 3%, nuclear: 4%) for the production of the fuel cell stack is of minor importance. For the NMVOC air emissions (26%) and cadmium soil emissions (80%) the production of the electronic components is an important source. Tab. 5.15 shows selected LCI results and cumulative energy demands for the manufacture of a 2 kW$_{el}$ PEM fuel-cell system.

Process “stack PEM fuel cell 2 kW$_{el}$, future ”

The major part of the fossile carbon dioxide (40%), nitrogen oxide (22%) and particulate < 2.5um emissions (17%) and the cumulative energy demand (fossil: 23%, nuclear: 44%) are caused by the electricity used for the stack production. Also an important part of the fossil carbon dioxide (22%), nitrogen oxide (41%) and particulate < 2.5um emissions (51%) and the cumulative energy demand (fossil: 31%, nuclear: 39%) are caused by the platin used for the stack. For the NMVOC air emissions direct emissions from the production (24%), the resin for the bipolar plates (31%) and the polymer membrane (21%) are most important. Tab. 5.15 shows selected LCI results and cumulative energy demands for the manufacture of a 2 kW$_{el}$ PEM fuel-cell stack.

Tab. 5.15 Selected LCI results and the cumulative energy demand for a 2kW$_{el}$ PEM fuel cell system

Ecocat	Ecosubcat	Name	Name	heat, natural gas, allocation exergy, at PEM fuel cell 2kWe, future	heat, biogas, allocation exergy, at PEM fuel cell 2kWe, future	electricity, natural gas, allocation exergy, at PEM fuel cell 2kWe, future	electricity, biogas, allocation exergy, at PEM fuel cell 2kWe, future	PEM fuel cell 2kWe, future	stack PEM fuel cell 2kWe, future	maintenance PEM fuel cell 2kWe
			Location	CH	CH	CH	CH	CH	CH	CH
			Unit	MJ	MJ	kWh	kWh	unit	unit	unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	3.37E-01	9.79E-02	1.20E+01	2.69E+00	3.16E+04	9.61E+02	8.93E+02
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	7.29E-03	5.10E-02	1.04E-01	1.81E+00	7.52E+03	3.24E+02	1.77E+02
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	4.51E-07	2.71E-07	1.60E-05	9.00E-06	4.68E-02	2.26E-03	2.41E-03
	water	renewable energy resources, water	MJ-Eq	1.48E-03	1.03E-02	3.11E-02	3.76E-01	1.54E+03	5.45E+01	3.40E+01
	biomass	renewable energy resources, biomass	MJ-Eq	4.12E-04	6.87E-04	7.20E-03	1.79E-02	3.61E+02	1.48E+01	1.48E+01
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	1.18E-04	2.51E-04	1.73E-03	6.90E-03	1.24E+02	5.58E+00	2.40E+00
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	1.70E-06	6.38E-06	2.42E-05	2.07E-04	1.80E+00	7.98E-02	3.75E-02
selected LCI results	resource	land occupation	m2a	8.65E-05	1.43E-04	1.76E-03	3.98E-03	6.58E+01	3.22E+00	3.26E+00
	air	CO2, fossil	kg	1.80E-02	5.67E-03	6.44E-01	1.62E-01	2.19E+03	9.82E+01	6.50E+01
	air	NMVOC	kg	1.17E-05	3.85E-06	3.89E-04	8.21E-05	1.43E+00	7.98E-02	7.61E-02
	air	nitrogen oxides	kg	1.14E-05	8.42E-06	3.00E-04	1.82E-04	3.73E+00	1.37E-01	1.28E-01
	air	sulphur dioxide	kg	1.99E-05	1.96E-05	5.93E-04	5.81E-04	1.30E+01	4.32E+00	1.85E+00
	air	particulates, <2.5 um	kg	1.11E-06	1.17E-06	1.79E-05	2.04E-05	9.71E-01	2.44E-02	2.49E-02
	water	BOD	kg	1.07E-05	1.04E-05	1.02E-04	8.71E-05	3.67E+00	2.44E-01	1.68E-01
	soil	cadmium	kg	6.48E-12	6.90E-12	2.25E-11	3.89E-11	2.10E-06	2.63E-08	2.43E-08

5.11 Conclusions

The LCI results show that the fuel and the emissions from the operation of the PEM fuel cell are for many elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 5.15) the production of the infrastructure is of high importance.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20-30% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are clearly higher with the use of biogas.

5.12 Appendices: EcoSpold Meta Information

Tab. 5.16 EcoSpold Meta Information of Co-generation with a 2kW$_{el}$ PEM fuel cell system

ReferenceFunction	Name	PEM fuel cell 2kWe, future	natural gas, burned in PEM fuel cell 2kWe, future	biogas, burned in PEM fuel cell 2kWe, future	stack PEM fuel cell 2kWe, future	maintenance PEM fuel cell 2kWe
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	1	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit	unit
DataSetInformatic	Type	1	5	5	1	1
	Version	2.0	2.0	2.0	2.0	2.0
	energyValues	0	0	0	0	0
	LanguageCode	en	en	en	en	en
	LocalLanguageCode	de	de	de	de	de
DataEntryBy	Person	72	72	72	72	72
	QualityNetwork	1	1	1	1	1
ReferenceFunctio	DataSetRelatesToProduct	1	1	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials the installation on the site.	The module includes fuel input, infrastructure and emissions to air.	The module includes fuel input, infrastructure and emissions to air.	The module includes the most important materials used for production. Also included is the transport of these materials and the energy needed for production.	The module includes an estimation for materials and transport used for the maintenance of the PEM fuel cell unit.
	Amount	1	1	1	1	1
	LocalName	PEM Brennstoffzelle 2kWel, zukünftig	Erdgas, in PEM Brennstoffzelle 2kWel, zukünftig	Biogas, in PEM Brennstoffzelle 2kWel, zukünftig	Zellenstapel PEM Brennstoffzelle 2kWel, zukünftig	Wartung PEM Brennstoffzelle 2kWel
	Synonyms	PEMFC//proton exchange membrane fuel cell//PEFC//polymer electrolyte fuel cell//Polymer Elektrolyt Membran Brennstoffzelle//Membran Brennstoffzelle	PEMFC//proton exchange membrane fuel cell//PEFC//polymer electrolyte fuel cell//Polymer Elektrolyt Membran Brennstoffzelle//Membran Brennstoffzelle	PEMFC//proton exchange membrane fuel cell//PEFC//polymer electrolyte fuel cell//Polymer Elektrolyt Membran Brennstoffzelle//Membran Brennstoffzelle	PEMFC//proton exchange membrane fuel cell//PEFC//polymer electrolyte fuel cell//Polymer Elektrolyt Membran Brennstoffzelle//Membran Brennstoffzelle	PEMFC//proton exchange membrane fuel cell//PEFC//polymer electrolyte fuel cell//Polymer Elektrolyt Membran Brennstoffzelle//Membran Brennstoffzelle
	GeneralComment	The module reflects a polymer electrolyte membrane (PEM) fuel cell with 2 kW electrical output. Inventory based on information from literature for future production based on manufacturer data. Life time operation is 15 years or 80'000 h. Stack replacement every 6th. year.	The multioutput-process 'natural gas, burned in PEM fuel cell 2kWe delivers the coproducts 'heat, natural gas, allocation exergy, at PEM fuel cell 2kWe' and 'electricity, natural gas, allocation exergy, at PEM fuel cell 2kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The multioutput-process 'biogas, burned in PEM fuel cell 2kWe delivers the coproducts 'heat, biogas, allocation exergy, at PEM fuel cell 2kWe' and 'electricity, biogas, allocation exergy, at PEM fuel cell 2kWe'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The module reflects a polymer electrolyte membrane (PEM) fuel cell stack with 2 kW electrical output. Inventory based on information from literature for future production based on manufacturer data. Life time operation is 6 years or 32'000 h.	The module reflects the maintenance for a polymer electrolyte membrane (PEM) fuel cell with 2 kW electrical output. Inventory based on information from literature for future production based on manufacturer data. Maintenance is carried out every year or 5'300 h. Every fourth year (21'000 h) reformer catalyst stack replacement and every sixth year (32'000 h) stack replacement is
	InfrastructureIncluded	1	1	1	1	1
	Category	natural gas	natural gas	biomass	natural gas	natural gas
	SubCategory	cogeneration	cogeneration	cogeneration	cogeneration	cogeneration
	LocalCategory	Erdgas	Erdgas	Biomasse	Erdgas	Erdgas
	LocalSubCategory	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	2000	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005	2005
	DataValidForEntirePeriod	1	1	1	1	1
	OtherPeriodText					

Tab. 5.16 (Part 2) EcoSpold Meta Information of Co-generation with a 2kW$_{el}$ PEM fuel cell system

ReferenceFunction	Name	PEM fuel cell 2kWe, future	natural gas, burned in PEM fuel cell 2kWe, future	biogas, burned in PEM fuel cell 2kWe, future	stack PEM fuel cell 2kWe, future	maintenance PEM fuel cell 2kWe
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	1	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit	unit
Geography	Text	Process applicable in central European conditions.	Natural gas input modelled for Switzerland. Process applicable in central European conditions.	Biogas input modelled for conditions in Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.	Process applicable in central European conditions.
Technology	Text	polymer electrolyte membrane (PEM) fuel cell for stationary cogeneration. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 32%, total efficiency 87%.	polymer electrolyte membrane (PEM) fuel cell for stationary cogeneration. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 32%, total efficiency 87%.	polymer electrolyte membrane (PEM) fuel cell for stationary cogeneration. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with refined biogas from low pressure gas network. Electrical efficiency 32%, total efficiency 87%.	polymer electrolyte membrane (PEM) fuel cell stack for stationary cogeneration. Performance, stack lifetime and catalyst use according to expected future values for serial production. Electrical efficiency 32%, total efficiency 87%.	polymer electrolyte membrane (PEM) fuel cell for stationary cogeneration. Performance, stack lifetime and catalyst use according to expected future values for a serial product. Operation with connection to low pressure gas network. Electrical efficiency 32%, total efficiency 87%.
Representativene	Percent					
	ProductionVolume	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information
	Extrapolations	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none
DataGeneratorAn	Person	72	72	72	72	72
	DataPublishedIn	2	2	2	2	2
	ReferenceToPublishedSource	47	47	47	47	47
	Copyright	1	1	1	1	1
	AccessRestrictedTo	0	0	0	0	0
	CompanyCode					
	CountryCode					
	PageNumbers	PEM fuel cell	PEM fuel cell	PEM fuel cell	PEM fuel cell	PEM fuel cell
ProofReading	Validator	42	42	42	42	42
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none	none	none

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6 Stirling Co-generation unit

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6.1 Introduction

Stirling engine based cogeneration systems in residential and commercial areas are of increasing interest because of their prospect for high total efficiency, fuel flexibility, low emission level, low vibration and noise level and good partial load performance. Due to fewer moving parts compared to reciprocating engines Stirling engines are expected to have low wear and long maintenance free operating periods.

Stirling engines usually operate with a continuous combustion process which takes place outside of the engine. Therefore the fuel-air mixture can be more accurately controlled and low emissions are achievable. Stirling engines can run directly on any available heat source, not just on combustion heat. There are systems available which run on heat from solar energy (dish-systems).

6.2 Characterisation of material product

The technology of Stirling engines is still in the development phase. Only few products which run on gaseous fuels are already on the market. Systems operating with solid fuels are so far only in pilot applications in operation. Beside a pilot production series of 3 kWel units which are currently in field tests (Sunmachine 2006) several manufacturers are developing Stirling engines for wood pellets or other biomass fuels. SOLO (2006b) is developing a wood pellet gasifier for it’s gas driven Stirling module with 9 kWel. Other manufacturers are developing a 1 kWel Stirling module for integration in a wood pellet boiler with a thermal output of 15-50 kW (SPM 2006, Hoval 2006). Larger modules for wood chips with an electrical power of up to 75 kWel are developed by Mawera (MAWERA 2005, Biedermann et al. 2004b).

6.3 Use / application of product

Stirling engines are attractive at power levels of less than 20 kWel, a range suitable for residential, and commercial areas (Knight et al., 2005). In these systems the external combustion process allows the use of a large fuel variety which includes solid fuels such as wood or other biomass. A system operated with wood pellets as fuel is described in this inventory. On the other hand the Stirling process can also be used as chiller. In this field of application the Stirling process is especially suited for low temperature applications (cryocooling).

6.4 System characterisation

Fig. 6.1 shows the system outline of the modelled Stirling co-generation unit. Wood pellets (acc. to Werner et al. 2003) are included as energy carriers to operate the Stirling unit.

Stirling engines can operate with different energy carriers. They are specially suitable for small scale cogeneration with solid fuels. For this field of application no other co-generation system is available. Stirling engines need an adapted combustor suitable for the combustion of solid fuels. Stirling engines with similar design may also be operated with natural gas (or biogas in natural gas quality).

A dataset of the heat production corresponding to each electricity dataset is also provided. Electricity production is given in kWh, heat production in MJ. It is assumed that the Stirling unit is operated in Switzerland (CH). However, the process is applicable also for central European conditions.

The infrastructure dataset refer to a Stirling co-generation unit as used in field tests in the year 2006.

The performance data for operation are based on actual target values specified by the manufacturer. These values may not yet be reached but this is likely to happen within the next 3-5 years. The emission levels used in the datasets are based on some test data, related processes and assumptions. So far no reliable measurements are available.

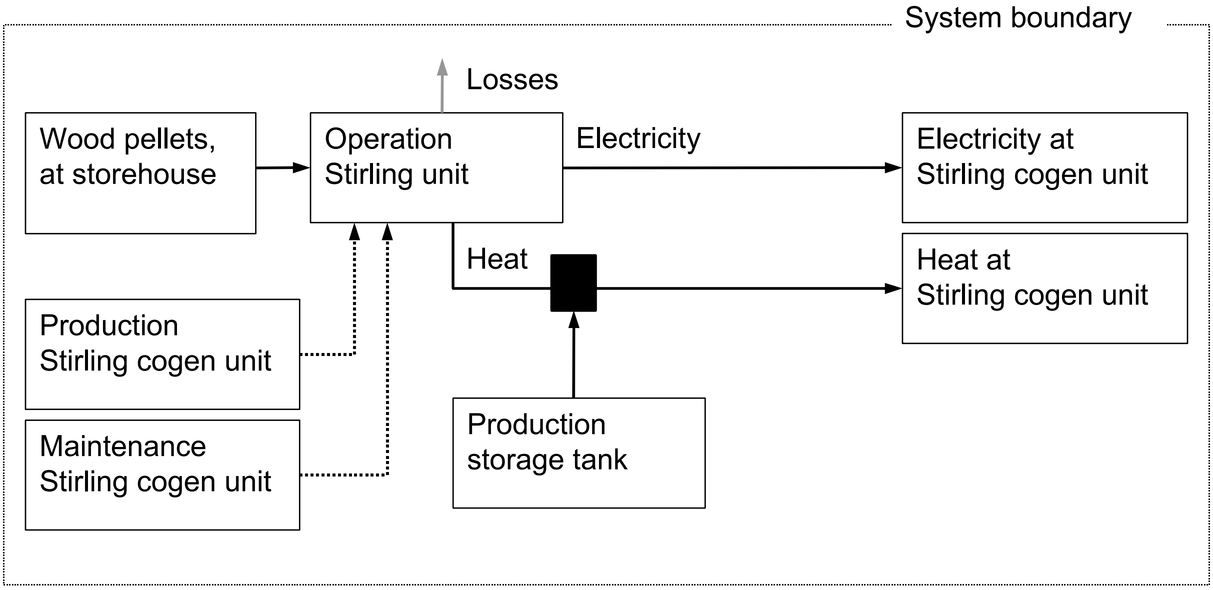

Fig. 6.1 System outline of a Stirling co-generation unit 3 kW_{el}

6.5 Wood pellets, burned in Stirling co-generation unit 3 kW_{el}

6.5.1 Technical characteristics

Stirling co-generation units for stationary applications are available with an electrical output of between 1 kWel and 75 kWel. A Stirling motor with a nominal output of 3 kWel and 10.5 kWth is analysed. The electric efficiency of Stirling co-generation units depends on the system design, the gas type and the pressure in the motor. For operation with natural gas an electric efficiency of 11 to 29 percent and a total efficiency of 80 to 96 percent are reached with Stirling units on the market (Knight et al. 2005, STM 2005, SOLO 2006a, Whisper Tech 2004). The lower value of the electric efficiency corresponds to a small system for single family homes (20 bar gas pressure, output: 1.2 kWel and 8 kWth) and the higher value to a large system with high working gas pressure (150 bar gas pressure, nominal output: 48 kWel, 78 kWth).

For operation with solid fuels such as wood pellets an electric efficiency of 20 to 25 percent and a total efficiency of 90 percent are expected (Sunmachine 2005, Biedermann et al. 2004a). The efficiency values are given on the basis of the lower heating value of the fuel.

The efficiency is dependent on the required supply and return temperature of the heating system. The efficiency values (electrical and total efficiency) increase when lower supply and return temperatures are applied. For every 1 Kelvin lower supply temperature the efficiency increases by 0.33% of the nominal value (Solo, 2006a).

Stirling co-generation units show a stable electrical efficiency for operation between 50 and 100 percent of the nominal load (SOLO 2006a). For heating systems with a supply temperature of 50°C or below the total efficiency is stable in the operating range. These data refer to a Stirling unit operated with natural gas. It is assumed that a similar performance is achieved for units operated with solid fuels such as wood pellets. Partial load operation is possible down to 30-40 percent of the nominal load.

An average electrical efficiency of 23 percent and a total efficiency of 90 percent are assumed for the operation of the 3 kW_{el} Stirling unit operated with wood pellets (see Tab. 6.1). The performance values used here are based on target values for serial products and not on values actually achieved in field tests.

Tab. 6.1 Electric and thermal efficiencies and losses of a 3 kW_{el} Stirling co-generation unit

Electricity generation	MJ/MJ_{in}	0.23
Heat generation	MJ/MJ_{in}	0.67
Total energy output	MJ/MJ_{in}	0.90
Heat losses	MJ/MJ_{in}	0.10
Waste heat, total *)	MJ/MJ_{in}	0.847
*) Based on HHV; wood pellets: HHV 13.1 MJ/ m^3; LHV = 12.2 GJ/m^3 (bulked volume) and including losses as well as heat generated		

6.5.2 Equipment and maintenance needed

The infrastructure needed is defined by the total operating life and the maintenance intervals of the unit. The target operating life of the Stirling co-generation unit is 80'000 hours and a maintenance interval every 5-8'000 hours is proposed (Sunmachine 2006, Knight et al. 2005, SOLO 2006a). An operating life of the Stirling co-generation unit of 15 years or 80’000 operating hours with 14 maintenance sessions during the operating life (maintenance every year) is assumed for the calculations.

For economic reasons, about 3’000 to 5’000 hours of full-load operation per year should be reached, which normally implies a bivalent system design with a peak load boiler. An operating life of 15 years or 5’333 operating hours per year and an average load factor of 67% is assumed, which leads to 3’573 hours of full-load operation per year. The fuel consumption is 13 kW at nominal load. Maintenance is needed every 0.18 TJ_{In} or 15 m^3 of pellet input (bulked volume; fourteen maintenance operations during the life time), and the operating life of the unit is reached after 2.52 TJ_{In} or 207 m^3 of pellet input (bulked volume).

Besides the infrastructure of the Stirling co-generation unit, which also includes the piping for the sanitary equipment and the planning, a storage tank is needed to ensure good system performance. A storage volume of 1 m^3 is assumed (Sunmachine 2006). The inventory of the storage tank is based on the 0.65 m^3 storage tank described in Heck (2003). As in Heck (2003), the operating life of the storage tank is 100’000 hours or 3.15 TJ_{In} or 258 m^3 of pellet input (bulked volume).

This inventory does not include the peak load boiler used in the system design as this depends strongly on the specific application.

The infrastructure processes included are summarised in Tab. 6.2.

Tab. 6.2 Equipment and maintenance of the 3 kW_{el} Stirling co-generation unit

Process	Operating life, interval	Amount
Stirling cogen unit 1kWe	80'000 h	3.97 E-7 units/MJ_{in}
Maintenance of Stirling cogen unit 1kWe	14 times per 80’000 h	5.56 E-6 units/MJ_{in}
Storage 650 l , *)	100'000 h	3.94 E-7 units/MJ_{in}
*) For 1 m^3 storage size 1.24 units are used.		

6.5.3 Energy and auxiliaries usage

Wood pellets consumption

As energy input wood pellets (u=10%, at storehouse) as described in Werner et al. (2003) are used. The volume refers to the bulked volume with a dried matter content of 650 kg/m^3 and a lower heating value of 12.2 GJ/m^3 (@ u=10%). For the calculations a pellet consumption (bulked volume) of $8.21*10^{-5}$ m^3/MJ_{In} is used.

Similar to the wood pellet boiler in Bauer (2003) 100 km transport distance or $5.87*10^{-3}$ tkm/MJ_{In} by lorry (3.5-20t, fleet average) is included for the fuel transport from the regional storehouse to the consumer.

Electricity demand for Start-up

For start up the Stirling motor has to be preheated to operating temperature. For this process grid electricity is needed (Sunmachine 2006). For each start of the cold engine about 0.75 kWh electricity is needed (15 Minutes start up time with 3 kWel). It is assumed that the average operating time between two starts is 12 hours of full-load operation (300 starts per year). This leads to an electricity demand from the grid of $1.34*10^{-3}$ kWh/MJ_{In}.

6.5.4 Emissions to Air

Due to the continuous combustion in Stirling engines these units have a low level of air emissions. No catalytic converter for emission reduction is needed because of the low emission level. Most emission data for Stirling motors are available for natural gas as fuel only. This emission data are summarised in Tab. 6.4. For solid fuels (e.g. wood pellets) especially particulate emissions are considerably higher. In order to avoid fouling in the heat exchanger a combustion process with very low dust emissions is used. The most important emission values used for operation with wood pellets and other solid fuels are summarised in Tab. 6.5.

The CO_2-emisions are calculated on the basis of the carbon content of the wood pellets. The values presented in Tab. 6.3 also take into account carbon emitted in the form of CO, CH_4 and NMVOC. According to Werner et al. (2003) the biogenic carbon content of wood pellets is 321 kg/m^3 (bulked volume) or 26.35 g/MJ_{In}.

Tab. 6.3 CO_2-emissions and carbon balance

	Emission factor	Carbon content	Share
Wood pellet input	-	321'100 g C / m^3 26'346.4 mg C / MJ_{In}	100.00 %
Carbon dioxide, biogenic	96'603.4 mg/MJ_{In}	26'346.4 mg C / MJ_{In}	99.94 %
Carbon monoxide, biogenic	32.0 mg/MJ_{In}	13.7 mg C / MJ_{In}	0.05 %
Methane, biogenic	0.4 mg/MJ_{In}	0.3 mg C / MJ_{In}	0.00 %
NMVOC *)	2.3 mg/MJ_{In}	1.9 mg C / MJ_{In}	0.01 %
*) Carbon content calculated as C5H12 (Pentane)			

The nitrogen oxide emissions depend on the temperatures of the combustion and the wood used. The emission data available from Stirling units operated with wood chips range in the same order of magnitude as the emission data of wood pellet boilers. A NO_X-emission factor of 70 mg/MJ_{In} is applied, as used for the 15 kW wood pellet boiler in Bauer (2003).

Carbon monoxide emissions are low (8 mg/MJ_{In}) when good combustion is achieved. This may not be the case under partial load conditions. Under such conditions carbon monoxide may rise similar to the combustion in conventional wood pellet boilers to levels of 0.2 g/MJ_{In} (KWB 2005) or more. It is assumed that partial load operation is avoided. It is assumed that high carbon monoxide emissions will only occur during start up or shut down. Average carbon monoxide emissions of 32 mg/MJ_{In} are consequently used here.

Due to missing information on hydrocarbon emissions the values for CH_4 and NMVOC emissions are approximated with data from the 15 kW wood pellet boilers described in Bauer (2003).

Only a few available sources state the particulate emissions of Stirling units operated with solid fuels. According to these sources, the emission level is similar compared to those of wood pellet boilers. Because low particulate emissions are crucial for an operation with low maintenance it is assumed that low emissions will be achieved. Therefore an emission factor of 10 mg PM2.5/MJ_{In} is used. This value is similar to the emission level of new pellet boilers (KWB, 2005).

As in Bauer (2003) it is assumed that these emissions are emitted as particles PM2.5.

No data are available for further emissions (e.g. N_2O or SO_2) from Stirling motors operated with wood pellets. These emissions are approximated by using identical emission factors as for the 15 kW wood pellet boiler described in Bauer (2003). The data used are shown in Tab. 6.5.

Tab. 6.4 Emissions to air of Stirling co-generation units operated with natural gas

NOx mg/MJ$_{In}$	CO mg/MJ$_{In}$	THC mg/MJ$_{In}$	Particulates mg/MJ$_{In}$	Type of fuel	Source
10-56 *)	4-35 *)	0-1.4 *)	-	Natural gas	SOLO (2006a)
35-68 **)	76	-	-	Natural gas	STM (2005)
7-35	3-35	1-35	-	Natural gas	Knight et al. (2005)
6.7	2	1	1.7	Natural gas	Krewitt et al. (2004)
13	70	< 1	-	Natural gas	Öberg et al. (2004)
18	35	< 3.5	-	-	Goldstein et al. (2003)
*) Lower value for optimised flox-burner **) Lower value for low emission burner					

Tab. 6.5 Emissions to air for 3 kW$_{el}$ Stirling co-generation unit operated with wood pellets

NOx mg/MJ$_{In}$	CO mg/MJ$_{In}$	CH_4 mg/MJ$_{In}$	NMVOC mg/MJ$_{In}$	Particulates mg/MJ$_{In}$	Type of fuel	Source
79	66	3.3	26	17	Wood chips	Probas (2005); *)
84	8	-	-	< 42	Wood chips	Obernberger (2004); **)
emission factors for wood pellet boilers (for aproximation)						
60-74	16-39	1-2		8-10	Wood chips	KWB (2005)
70	96	0.4	2.3	26	Wood chips	Bauer (2003)
70	**32**	**0.4**	**2.3**	**10 (PM 2.5)**	**Wood pellets**	**used in this inventory**
*) Emission data based on Stirling project of MAWERA 2005. **) Emission data based on measured data on 35kWel Stirling operated with wood chips (52% water content)						

6.5.5 Ash disposal

Besides the air emissions ash from the combustion of the wood pellets occurs. Depending on the design of the Stirling unit this ash has to be removed periodically or will be disposed of with condensed water. A disposal of the ash to a municipal incineration plant is assumed. According to Bauer (2003) 0.5% of the wood pellet input (dry weight) has to be disposed of as ash. According to the wood pellet input (see chapter 6.5.3) 266 mg/MJ$_{In}$ ash is disposed of.

6.5.6 Allocation

The energy input, emissions and infrastructure expenditures are allocated to the following products:

- heat, pellets, allocation exergy, at Stirling cogen unit 3 kWe, future
- electricity, pellets, allocation exergy, at Stirling cogen unit 3 kWe, future

Various allocation concepts may be applied and are discussed in Heck (2003). The exergy content is applied in this project. An allocation based on exergy leads to higher specific requirements and emissions per kWh of electricity compared to 1 kWh of heat. The allocation factors are determined according to the calculation presented in Heck (2003). The resulting allocation factors and underlying assumptions are summarised in Tab. 6.6.

Tab. 6.6 Allocation factors applied to electricity and heat production, based on exergy

	Electricity	Heat	Total
Efficiency	23 %	67 %	90 %
Exergy factor *)	1.000	0.093	-
Allocation factor	78.8 %	21.2 %	100.0 %
*) Based on a hot water temperature of 60/40 °C and an ambient temperature of 20 °C for heat production			

6.5.7 Data quality considerations

Tab. 6.7 shows the multi-output process raw data and data-quality indicators of the inventory of wood pellets, burned in a 3 kW_{el} Stirling cogen unit, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is not based on measurements, but merely represents information available from the manufacturers of such fuel cells. Because these systems have so far operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached within the next 5 years.

Tab. 6.7 Multi-output process raw data of wood pellets, burned in Stirling cogen unit 3 kW_{el}, future

	Name	Location	Infrastructure Process	Unit	wood pellets, burned in stirling cogen unit 3kWe, future	UncertaintyType	Standard Deviation 95%	GeneralComment	heat, pellets, allocation exergy, at stirling cogen unit 3kWe, future	electricity, pellets, allocation exergy, at stirling cogen unit 3kWe, future
	Location				CH				CH	CH
	InfrastructureProcess				0				0	0
	Unit				MJ				MJ	kWh
allocated	heat, pellets, allocation exergy, at stirling cogen unit 3kWe, future	CH	0	MJ	6.70E-1				100	0
	electricity, pellets, allocation exergy, at stirling cogen unit 3kWe, future	CH	0	kWh	6.39E-2				0	100
technosphere	stirling cogen unit 3kWe, wood pellets, future	CH	1	unit	3.97E-7	1	3.07	(3,4,2,1,1,5); uncertainty of life time	21.2	78.8
	maintenance stirling cogen unit 3kWe, wood pellets, future	CH	0	unit	5.56E-6	1	3.07	(3,4,2,1,1,5); uncertainty of maintenance cycle	21.2	78.8
	storage 650 l Mini-BHKW	CH	1	unit	3.94E-7	1	3.02	(2,3,2,1,1,4); uncertainty of life time	100.0	-
	wood pellets, u=10%, at storehouse	RER	0	m3	8.21E-5	1	1.10	(2,2,2,1,1,3); uncertainty on energy and water content, and bulk density	21.2	78.8
	electricity, low voltage, at grid	CH	0	kWh	1.34E-3	1	1.26	(3,4,1,1,1,5); company data	21.2	78.8
	transport, lorry 3.5-20t, fleet average	CH	0	tkm	5.87E-3	1	2.02	(2,3,2,1,1,4); data from wood pellet boiler	21.2	78.8
	disposal, wood ash mixture, pure, 0% water, to municipal incineration	CH	0	kg	2.66E-4	1	1.51	(2,nA,nA,nA,4,nA); calculated from pellet input	21.2	78.8
emission air, high population density	Acetaldehyde	-	-	kg	6.10E-8	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Ammonia	-	-	kg	1.73E-6	1	1.73	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Arsenic	-	-	kg	1.00E-9	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Benzene	-	-	kg	9.10E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Benzene, ethyl-	-	-	kg	3.00E-8	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Benzene, hexachloro-	-	-	kg	7.20E-15	1	3.36	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Benzo(a)pyrene	-	-	kg	5.00E-10	1	3.36	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Bromine	-	-	kg	6.00E-8	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Cadmium	-	-	kg	7.00E-10	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Calcium	-	-	kg	5.85E-6	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Carbon dioxide, biogenic	-	-	kg	9.66E-2	1	1.07	(2,nA,nA,nA,1,nA); calculated from composition of wood pellets	21.2	78.8
	Carbon monoxide, biogenic	-	-	kg	3.20E-5	1	5.29	(2,4,2,1,4,4); estimate based on larger unit or other technology	21.2	78.8
	Chlorine	-	-	kg	1.80E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Chromium	-	-	kg	3.96E-9	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Chromium VI	-	-	kg	4.00E-11	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Copper	-	-	kg	2.20E-8	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8

Tab 6.7 (Part 2) Multi-output process raw data of wood pellets, burned in Stirling cogen unit 3 kW$_{el}$, future

	Name	Location	Infrastructure Process	Unit	wood pellets, burned in stirling cogen unit 3kWe, future	UncertaintyType	Standard Deviation 95%	GeneralComment	heat, pellets, allocation exergy, at stirling cogen unit 3kWe, future	electricity, pellets, allocation exergy, at stirling cogen unit 3kWe, future
	Location InfrastructureProcess Unit				CH 0 MJ				CH 0 MJ	CH 0 kWh
emission air, high population density	Dinitrogen monoxide	-	-	kg	3.00E-6	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	3.10E-14	1	3.36	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Fluorine	-	-	kg	5.00E-8	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Formaldehyde	-	-	kg	1.30E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Hydrocarbons, aliphatic, alkanes, unspecified	-	-	kg	9.10E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Hydrocarbons, aliphatic, unsaturated	-	-	kg	3.10E-6	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Lead	-	-	kg	2.50E-8	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Magnesium	-	-	kg	3.60E-7	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Manganese	-	-	kg	1.70E-7	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Mercury	-	-	kg	3.00E-10	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Methane, biogenic	-	-	kg	4.00E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	m-Xylene	-	-	kg	1.20E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Nickel	-	-	kg	6.00E-9	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Nitrogen oxides	-	-	kg	7.00E-5	1	1.81	(2,4,2,1,4,4); estimate based on larger unit or other technology	21.2	78.8
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.30E-6	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	1.11E-8	1	3.36	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Particulates, < 2.5 um	-	-	kg	1.00E-5	1	3.33	(4,4,2,1,4,5); estimate based on other technology	21.2	78.8
	Phenol, pentachloro-	-	-	kg	8.10E-12	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Phosphorus	-	-	kg	3.00E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Potassium	-	-	kg	2.34E-5	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Sodium	-	-	kg	1.30E-6	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Sulfur dioxide	-	-	kg	2.50E-6	1	1.68	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Toluene	-	-	kg	3.00E-7	1	1.93	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Zinc	-	-	kg	3.00E-7	1	5.42	(4,5,2,1,4,5); estimate based on data for wood boiler	21.2	78.8
	Heat, waste	-	-	MJ	8.52E-1	1	1.11	(2,3,2,1,1,3); uncertainty of heating value and electric efficiency	21.2	78.8

6.6 Manufacture of a Stirling co-generation unit 3 kW$_{el}$

6.6.1 Technical characteristics

The infrastructure dataset of the the 3 kW$_{el}$ Stirling co-generation unit includes the most important materials used for its production, the transport of these materials and the energy needed for its production and engineering. The production process involves various steps including raw material cutting, casting, machining and welding. Steel is the principal material used, others being stainless steel (burner housing), copper (generator) and aluminium. The total weight of the analysed unit is 350 kg.

6.6.2 Infrastructure

No data are available on the production infrastructure for Stirling units. The infrastructure size is approximated with a production facility for similar products (Viessmann 2005). This production site includes 35,300 m^2 of floor space (offices, production and storage). An output of 29’000 units per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17,700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105,900 m^3. The service life of the buildings is assumed to be 50 years. Each unit bears the environmental burdens of 0.012 m^2 of the building hall and 0.073 m^3 of the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with the data of a similar production site (Viessmann 2005). On this site, 63,500 m^2 is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation period. Each unit bears the environmental burdens of 0.044 m^2 of land transformation and 2.19 m^2 a of land occupation.

6.6.3 Raw materials, energy and auxiliaries

The amount of raw materials used for the production of the 3 kW$_{el}$ Stirling co-generation unit is derived from Krewitt et al. (2004). In this data only the material for the Stirling unit is included and neither energy demand for the production process nor transport requirements are considered. On the other hand 0.354g platinum is included for a catalyst. According to Sunmachine (2006) no catalyst is used. Therefore no platinum demand is accounted.

For each Stirling co-generation unit (3 kWel), an additional energy requirement of 1.34 GJ for heat (natural gas, at industrial furnace >100 kW) and 186 kWh of electricity (medium voltage, production UCTE, at grid) is included for heating and electricity on the production site. The amount used is based on the specific energy requirement per kg product of a similar production site (Viessmann 2005).

No data are available on the water consumption for manufacturing the Stirling co-generation unit. The amount used (see Tab. 6.8) is based on the specific water requirement of 1.22 litre per kg of product of a similar production site (Viessmann 2005).

For the transportation of the raw materials, the standard distances for Europe according to (Frischknecht et al., 2004) are applied. For metals and plastics, 200 km for rail transport and 100 km for road transport (lorry >16t, fleet average) are used here. These distances are also applied to the fuel cell stack because it is not manufactured at the same location as the total unit. For the installation of the unit, a distance of 200 km by road transport is assumed (lorry >16t, fleet average).

Additional material and energy is needed for the auxiliary installations (e.g. sanitary ducting). These parts are modelled with the dataset “heating, sanitary equipment Mini-BHKW” described in Heck (2003). In view of the larger size of the CHP unit described in Heck (2003), only 75% of this amount is used.

Additional energy is consumed for planning and engineering. For the 3 kW$_{el}$ unit 20 working hours of planning and engineering are assumed. On the basis of data from Aebischer and Catenazzi (2006), a specific energy consumption of 15 MJ/h of heat (light fuel oil burned in a 100 kW non-modulating boiler) and 2 kWh/h of electricity (low voltage, at grid, CH) is used to calculate the energy requirement. Moreover, it is assumed that the construction site is visited twice and the distance of 200 km (return trip) for each visit is covered by car.

The data used in the inventory are shown in Tab. 6.8.

Tab. 6.8 Raw materials, energy and auxiliaries of the manufacture of a 3 kW$_{el}$ Stirling co-generation unit

Size of the Stirling unit (nominal electrical power)	Unit -	Used in this study 3 kW$_{el}$	Remarks	
Reinforcing steel, at plant	kg	136		R
Chromium steel 18/8, at plant	kg	31	1)	R
Cast iron, at plant	kg	148		R
Copper, at regional storage	kg	4.5		R
Aluminium, production mix, wrought alloy, at plant	kg	2.4		R
Lead, at regional storage	kg	0.12		R
Nickel, 99.5%, at plant	kg	0.06		R
Tin, at regional storage	kg	0.26		R
Zinc for coating, at regional storage	kg	0.04		R
Platinum, at regional storage	kg	0	2)	R
Polyethylene, HDPE, granulate, at plant	kg	12.6		I
Polyvinylchloride, at regional storage	kg	1.2		I
Ceramic tiles, at regional storage	kg	0.5	3)	L
Rock wool, packed, at plant	kg	12		L
Sheet rolling, steel	kg	136	4)	
Sheet rolling, chromium steel	kg	31	4)	
Sheet rolling, aluminium	kg	2.4	4)	
Wire drawing, copper	kg	4.2	4)	
Transport, freight, rail, RER	tkm	70		
Transport, lorry >16t, fleet average, RER	tkm	105		
Heating, sanitary equipment Mini-BHKW (5 kWel)	unit	0.75		
Water for manufacturing (unspecified natural origin)	m3	0.427		W
Heating production site: natural gas, at industrial furnace >100kW	MJ	1340		
Electricity production site: medium voltage, production UCTE, at grid	kWh	186		
Heating engineering services: light fuel oil, burned in boiler 100kW, non-modulating	MJ	300		
Electricity engineering services: low voltage, at grid, at grid, CH	kWh	40		
Transport engineering: transport, passenger car, CH	pkm	400		
Dismantling: R = Recycling; I = Disposal in municipal incineration plant; L = Landfilled; W = Disposal in wastewater plant 1) High temperature parts as chromium steel accounted (according to Krewitt et al (2004) low alloyed steel) 2) According to Sunmachine (2006) no catalyst is used. Platinum demand according to Krewitt et al (2004) is neglected. 3) Own assumption for ceramic pellet burner roast 4) For pre-fabrication of used raw material				Dismantling

6.6.4 Emissions to air and water

Emissions to air are included in the processes unit used (e.g. heating or transport processes). No further process-related air emissions occur. An average wastewater treatment process is used for the wastewater disposal due to a lack of data on water emissions from manufacturing. It is assumed that all the fresh water used is disposed of as wastewater via a suitable treatment plant. The amount and type of disposal of the various materials is indicated in Tab. 6.8.

6.6.5 Dismantling

After their service life, the Stirling unit will be dismantled and the materials recycled or disposed of. It is assumed that all metals will be recycled. No environmental burdens from dismantling and recycling are included (cut-off) for these materials. Final disposal of the plastic materials in a municipal incineration plant is assumed. The amount and type of disposal of the different stack materials is indicated in Tab. 6.8. Depending on the waste treatment process additional water content of the waste is added to the weight of the disposed material (e.g. for rock wool and ceramic tiles). The value used in Tab. 6.9 includes the water content of the waste.

6.6.6 Data quality considerations

Tab. 6.9 shows the unit process raw data and data-quality indicators of the manufacture of a Stirling co-generation unit with 3 kW_{el} electrical nominal power.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty is adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for various additional processes not covered in the data source. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 6.9 Unit process raw data of the manufacture of a 3 kW_{el} Stirling co-generation unit

	Name	Location	InfrastructureProcess	Unit	stirling cogen unit 3kWe, wood pellets, future	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	stirling cogen unit 3kWe, wood pellets, future	CH	1	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	1.36E+2	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	cast iron, at plant	RER	0	kg	1.48E+2	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	chromium steel 18/8, at plant	RER	0	kg	3.10E+1	1	1.26	(3,4,2,2,1,5); data from pilot plant design, assumption
	copper, at regional storage	RER	0	kg	4.50E+0	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	aluminium, production mix, wrought alloy, at plant	RER	0	kg	2.40E+0	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	lead, at regional storage	RER	0	kg	1.20E-1	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	nickel, 99.5%, at plant	GLO	0	kg	6.00E-2	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	tin, at regional storage	RER	0	kg	2.60E-1	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	zinc, primary, at regional storage	RER	0	kg	4.00E-2	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.26E+1	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	polyvinylchloride, at regional storage	RER	0	kg	1.20E+0	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	ceramic tiles, at regional storage	CH	0	kg	5.00E-1	1	1.32	(4,4,1,1,1,5); estimation
	rock wool, packed, at plant	CH	0	kg	1.20E+1	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	sheet rolling, steel	RER	0	kg	1.36E+2	1	1.25	(2,4,2,2,1,5); data from pilot plant design
	sheet rolling, chromium steel	RER	0	kg	3.10E+1	1	1.25	(2,4,2,2,1,5); based on material input
	sheet rolling, aluminium	RER	0	kg	2.40E+0	1	1.25	(2,4,2,2,1,5); based on material input
	wire drawing, copper	RER	0	kg	4.20E+0	1	1.25	(2,4,2,2,1,5); based on material input
	heating, sanitary equipment Mini-BHKW	CH	1	unit	7.50E-1	1	3.16	(4,4,2,5,3,5); approximation based on similar process
	transport, freight, rail	RER	0	tkm	7.00E+1	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	1.05E+2	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, passenger car	CH	0	pkm	4.00E+2	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	1.34E+3	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	3.00E+2	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.86E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	electricity, low voltage, at grid	CH	0	kWh	4.00E+1	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	1.26E+1	1	1.35	(2,4,3,2,3,5); approximation for disposal of plastic parts
	disposal, building, polyvinylchloride products, to final disposal	CH	0	kg	1.20E+0	1	1.35	(2,4,3,2,3,5); approximation for disposal of plastic parts
	disposal, building, mineral wool, to final disposal	CH	0	kg	1.20E+1	1	1.35	(2,4,3,2,3,5); approximation for disposal of insulation material
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	5.25E-1	1	1.32	(4,4,1,1,1,5); based on material input of ceramic parts
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	4.27E-1	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	7.30E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
	building, hall, steel construction	CH	1	m2	1.20E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data
resource, in water	Water, unspecified natural origin	-	-	m3	4.27E-1	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	2.19E+0	1	1.65	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, from unknown	-	-	m2	4.40E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
	Transformation, to industrial area, built up	-	-	m2	4.40E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data
emission air, high population density	Heat, waste	-	-	MJ	8.14E+2	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

6.7 Maintenance Stirling co-generation unit 3 kW$_{el}$

6.7.1 Technical characteristics

The dataset representing the maintenance of the Stirling co-generation includes the estimated material use and transport services for these activities. Stirling motors have the potential for low maintenance requirements. The target is, that no maintenance of the motor itself is needed during the operating life of the unit. Regular replacement of the pellet burner roast (ceramic parts) and cleaning of the heat exchanger is needed.

6.7.2 Raw materials, energy and auxiliaries

It is assumed that within the yearly maintenance the pellet burner roast (0.5 kg ceramics) and further parts of the unit are replaced (mainly steel). The amount of this additional material is estimated to 1% of the total plant weight (= 3.5 kg). It is assumed that the service personnel travels 200 km for each service.

6.7.3 Emissions to air

Emissions to air are included in the unit processes used (e.g. transport processes). No further process-related air emissions occur.

6.7.4 Dismantling

It is assumed that all metals (3.5 kg) will be recycled. For those materials, no burdens from dismantling and recycling are included (cut-off). The ceramic roast is landfilled (0.5 kg, 0.525 kg including 5% water content of the waste).

6.7.5 Data quality considerations

Tab. 6.10 shows the unit process raw data and data-quality indicators of the maintenance of a 3 kW$_{el}$ Stirling co-generation unit.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. The inventory is based on only a rough estimate for the process. Large uncertainties exist for the transport distances and the amount of material used. In general, therefore, the data quality is not very reliable.

Tab. 6.10 Unit process raw data of the maintenance of a 3 kW$_{el}$ Stirling co-generation unit

	Name	Location	InfrastructureProce	Unit	maintenance stirling cogen unit 3kWe, wood pellets, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				unit			
product	maintenance stirling cogen unit 3kWe, wood pellets, future	CH	0	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	3.50E+0	1	1.38	(4,5,n.A.,n.A.,1,5); estimate
	ceramic tiles, at regional storage	CH	0	kg	5.00E-1	1	1.38	(4,5,n.A.,n.A.,1,5); estimate based on expectation of manufacturer
	transport, passenger car	CH	0	pkm	2.00E+2	1	2.14	(4,5,n.A.,n.A.,1,5); estimated
	disposal, inert waste, 5% water, to inert material landfill	CH	0	kg	5.25E-1	1	1.38	(4,5,n.A.,n.A.,1,5); based on material input

6.8 Cumulative results and interpretation

6.8.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Multi-output process “ wood pellets, burned in Stirling cogen unit 3 kW$_{el}$, future”

The major part of the nitrogen oxide (65%) and particulate < 2.5um emissions (72%) are caused by direct emissions from operation. Also a smaller part of the NMVOC emissions (20%) are caused by direct emissions from operation. The major part of the fossil carbon dioxide (69%), NMVOC (46%), nitrogen oxide (19%) and particulate < 2.5um emissions (18%) and the cumulative energy demand (biomass: 100%, fossil: 65%, nuclear: 79%) are caused by the wood pellets used for operation. Further an important part of the fossil carbon dioxide (14%), NMVOC (21%), nitrogen oxide (13%) and particulate < 2.5um emissions (4%) and of the cumulative fossil energy demand (16%) are caused by the transport of the wood pellets. The manufacture of the Stirling co-generation unit is for the fossil carbon dioxide emissions (9%) and the cumulative fossil energy demand (10%) of importance. Tab. 6.11 shows selected LCI results and cumulative energy demands for electricity and heat production with a Stirling co-generation unit. The results depend significantly on the chosen allocation method.

Process “ Stirling cogen unit 3 kW$_{el}$, future”

The major part of the emissions and cumulative energy demand are caused by the material (especially steel) and energy used for the production of the auxiliary systems of the Stirling co-generation unit (e.g. heating, sanitary equipment). The electricity used for the production of the Stirling engine makes up 13% of the cumulative nuclear energy demand. Tab. 6.11 shows selected LCI results and cumulative energy demands for the manufacture of a 3 kW$_{el}$ Stirling cogen unit.

Tab. 6.11 Selected LCI results and the cumulative energy demand for Stirling co-generation unit

Ecocat	Ecosubcat	Name	Name	heat, pellets, allocation exergy, at stirling cogen unit 3kWe, future	electricity, pellets, allocation exergy, at stirling cogen unit 3kWe, future	stirling cogen unit 3kWe, wood pellets, future	maintenance stirling cogen unit 3kWe, wood pellets, future
			Location	CH	CH	CH	CH
			Unit	MJ	kWh	unit	unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	6.42E-02	1.88E+00	3.92E+04	6.55E+02
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	2.71E-02	9.57E-01	8.21E+03	8.30E+01
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	7.94E-08	2.24E-06	3.86E-02	1.59E-03
	water	renewable energy resources, water	MJ-Eq	3.61E-03	1.26E-01	1.50E+03	1.58E+01
	biomass	renewable energy resources, biomass	MJ-Eq	3.42E-01	1.33E+01	3.86E+02	2.26E+00
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	4.34E-04	1.53E-02	1.36E+02	7.24E-01
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	6.47E-06	2.29E-04	1.98E+00	1.35E-02
selected LCI results	resource	land occupation	m2a	8.78E-03	3.41E-01	7.38E+01	1.66E+00
	air	CO2, fossil	kg	4.33E-03	1.36E-01	2.61E+03	4.24E+01
	air	NMVOC	kg	6.25E-06	2.06E-04	1.31E+00	5.95E-02
	air	nitrogen oxides	kg	3.59E-05	1.32E-03	4.46E+00	8.68E-02
	air	sulphur dioxide	kg	1.31E-05	4.08E-04	6.38E+00	7.13E-02
	air	particulates, <2.5 um	kg	4.67E-06	1.68E-04	1.02E+00	1.31E-02
	water	BOD	kg	9.08E-06	1.79E-04	3.49E+00	1.11E-01
	soil	cadmium	kg	1.01E-11	2.67E-10	5.30E-07	1.71E-08

6.9 Conclusions

The LCI results show that the fuel and the emissions from the operation of the SOFC-GT fuel cell are for many elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 6.11) the production of the infrastructure is of high importance.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20-25% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are clearly higher with the use of biogas.

6.10 Appendices: EcoSpold Meta Information

Tab. 6.12 EcoSpold Meta Information of Stirling co-generation unit with 3 kWhel

ReferenceFunction	Name	stirling cogen unit 3kWe, wood pellets, future	wood pellets, burned in stirling cogen unit 3kWe, future	maintenance stirling cogen unit 3kWe, wood pellets, future
Geography	Location	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0
ReferenceFunctio	Unit	unit	MJ	unit
DataSetInformatic	Type	1	5	1
	Version	2.0	2.0	2.0
	energyValues	0	0	0
	LanguageCode	en	en	en
	LocalLanguageCode	de	de	de
DataEntryBy	Person	72	72	72
	QualityNetwork	1	1	1
ReferenceFunctio	DataSetRelatesToProduct	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials the installation on the site.	The module includes fuel input, infrastructure, emissions to air, and working materials for operation.	The module includes an estimation for materials and transport used for the maintenance of the Stirling cogeneration unit
	Amount	1	1	1
	LocalName	Stirlingmotor 3kWel, Holzpellets, zukünftig	Holzpellets, in Stirlingmotor 3kWel, zukünftig	Wartung Stirlingmotor 3kWel, Holzpellets, zukünftig
	Synonyms			
	GeneralComment	The module reflects a Stirling cogeneration unit with 3 kW electrical output. Operation of the unit with wood pellets. Inventory based on information of a pilot unit from literature and from one manufacturer. Life time operation is 80'000 h or 15 years.	The multioutput-process 'wood pellets, burned in Stirling cogen unit 1kWe, future" delivers the coproducts 'heat, pellets, allocation exergy, at Stirling cogen unit 3kWe, future' and 'electricity, pellets, allocation exergy, at Stirling cogen unit 3kWe, future'. The exergy allocation is the allocation scheme suggested to be used within the ecoinvent database (e.g. in electricity mixes).	The module reflects the maintenance for a Stirling cogeneration unit with 3 kW electrical output. Operation of the unit with wood pellets. Inventory based on estimations and information from one manufacturer. Maintenance is carried out every year or 5'300 h. Life time operation is 15 years or 80'000 h.
	InfrastructureIncluded	1	1	1
	Category	biomass	biomass	biomass
	SubCategory	cogeneration	cogeneration	cogeneration
	LocalCategory	Biomasse	Biomasse	Biomasse
	LocalSubCategory	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)	Wärmekraftkopplung (WKK)
	Formula			
	StatisticalClassification			
	CASNumber			
TimePeriod	StartDate	2000	2000	2000
	EndDate	2005	2005	2005
	DataValidForEntirePeriod	1	1	1
	OtherPeriodText			
Geography	Text	Process applicable in central European conditions.	Wood pellet input modelled for Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.
Technology	Text	Stirling motor for combustion of wood pellets. Power range: 1-3 kW electrical output, 4.5-10.5 kW heat output. Includes pellet storage volume for one day of operation. Electrical efficiency 23%, total efficiency 90%. Performance and lifetime according to expected future values for a serial product.	Stirling motor for combustion of wood pellets. Power range: 1-3 kW electrical output, 4.5-10.5 kW heat output. Includes pellet storage volume for one day of operation. Electrical efficiency 23%, total efficiency 90%. Performance and lifetime according to expected future values for a serial product. Emission values based on similar processes and assumptions due to yet missing emission measurements.	Stirling motor for combustion of wood pellets. Power range: 1-3 kW electrical output, 4.5-10.5 kW heat output. Includes pellet storage volume for one day of operation. Electrical efficiency 23%, total efficiency 90%. Performance, lifetime and maintenance intervall according to expected future values for a serial product.
Representativene	Percent			
	ProductionVolume	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information	Literature data and manufacturer information
	Extrapolations	none	none	none
	UncertaintyAdjustments	none	none	none
DataGeneratorAn	Person	72	72	72
	DataPublishedIn	2	2	2
	ReferenceToPublishedSource	47	47	47
	Copyright	1	1	1
	AccessRestrictedTo	0	0	0
	CompanyCode			
	CountryCode			
	PageNumbers	Stirling Co-generation unit	Stirling Co-generation unit	Stirling Co-generation unit
ProofReading	Validator	42	42	42
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none

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7 Absorption chiller and absorption heat pump

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7.1 Introduction

Absorption cooling is often used in conjunction with combined heat and power units because, although there is often no use for the heat produced during the summer, there is a cooling requirement. The absorption cycle is a process by which a refrigeration effect is produced through the use of two fluids and a certain heat input. This process can also operate in the reverse direction as a heat pump.

This inventory covers an absorption chiller with 100 kW cooling capacity and a small diffusion-absorption heat pump ($4kW_{th}$) which could be used for heating detached houses in future.

7.2 Characterisation of material product

Absorption cooling machines are commercially available today in two basic configurations. For applications above 0°C (primarily air conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant. For applications below 0°C, an ammonia/water cycle is used with ammonia as the refrigerant and water as the absorbent (Kevin and Rafferty, 1998).

Diffusion-absorption heat pumps are not yet on the market. Buderus is developing a heat pump of this kind which can operate in conjunction with a low-temperature heat source such as an earth collector or a simple air/water collector installed on a roof.

7.3 Use / application of product

Absorption cooling with the lithium bromide/water cycle is used for HVAC applications in commercial and residential buildings. Most commercial and industrial refrigeration applications involve process temperatures of less than 0°C, and many as low as –18°C. As a result, the lithium bromide/water cycle can no longer meet the requirements, because water cannot be cooled below 0°C (Kevin and Rafferty, 1998).

Waste heat from various processes (such as municipal incineration) or from co-generation units may be used as a heat source for absorption cooling. In the last few years, solar heat has been used for cooling applications with absorption chillers such as that investigated by Beuchat et al. (2005).

Diffusion-absorption heat pumps will be used mainly in residential buildings and may become a new competitor for electrical heat pumps or condensing gas heaters.

7.4 System characterisation

Fig. 7.1 shows the system outline of the modelled **D**iffusion **A**bsorption **H**eat **P**ump system (DAHP). It is assumed that the turbine is connected to the Swiss and European low-pressure gas network (Faist Emmenegger et al. 2003). Natural gas (Faist Emmenegger et al. 2003) and biogas (Jungbluth et al. 2007) are included as energy carriers to operate the heat pump.

Very different heat sources may be used for absorption cooling. For the inventory presented in this report heat of a cogeneration unit is used as example (Fig. 7.2). The infrastructure process refers to an absorption cooling unit with 100 kW cooling capacity and a hybrid air cooler.

The infrastructure dataset of the diffusion-absorption heat pump refers to a unit with 4 kW_{th} of nominal thermal power connected to a short-borehole heat exchanger. The unit includes a peak-load boiler which allows a maximum output power of 11 kW_{th}. The performance data for operation are based on actual target values given by the manufacturer. These values may not be reached until the unit goes into series production. Because no emission values are yet available, the emission levels used in the datasets are based on condensing gas boilers. However, the unit will operate with similar technology.

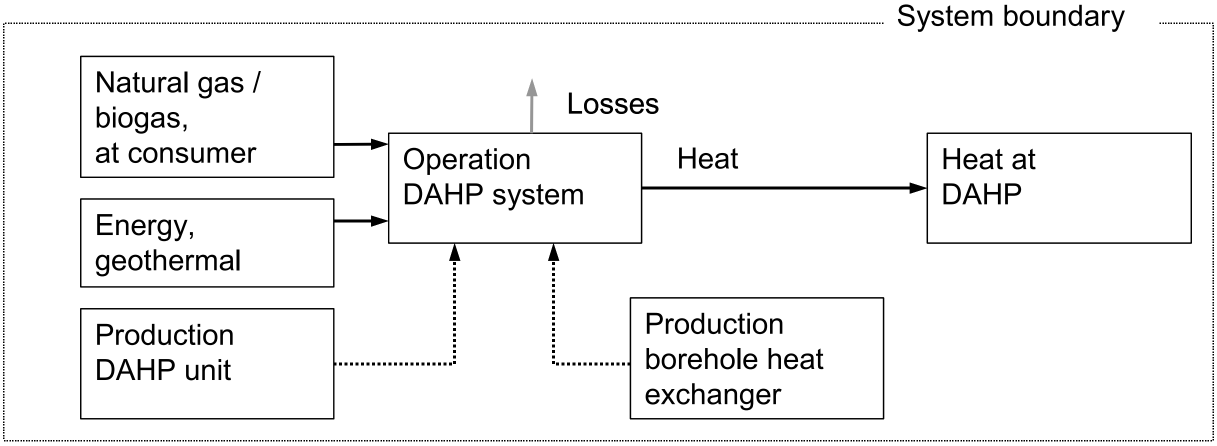

Fig. 7.1 System outline of a 4kW_{th} diffusion-absorption heat pump

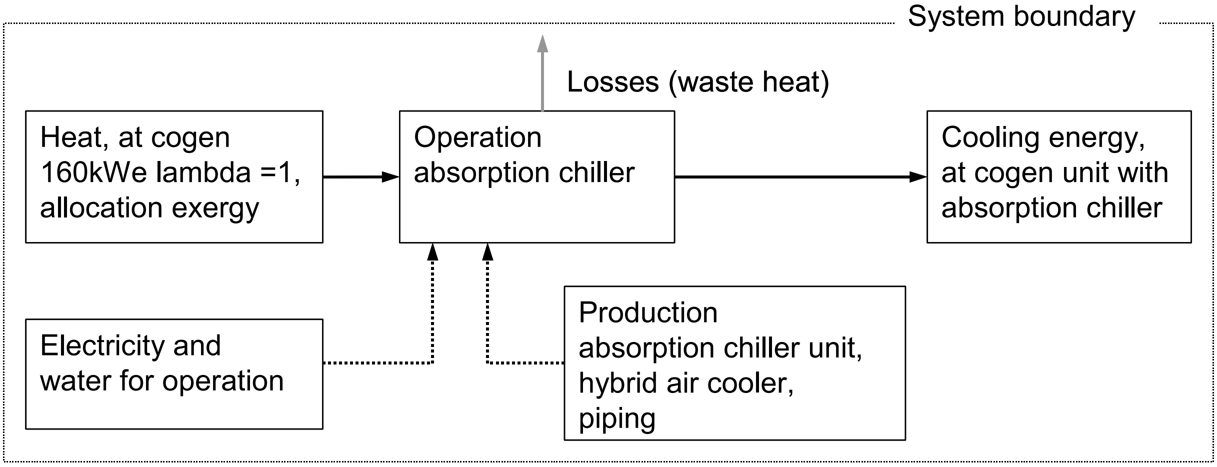

Fig. 7.2 System outline of a 100kW absorption chiller

7.5 Heat, natural gas, at diffusion absorption heat pump 4 kW

7.5.1 Technical characteristics

According to Stahlberg and Wolf (2001), the analysed system has a seasonal performance factor (SPF) of 1.32 when the peak-load boiler, which is included in the system, is taken into account. This value depends on the temperature of the heat source (air, geothermal, solar) as well as on the supply temperature of the heating system. If the diffusion-absorption heat pump is operated without a peak-load boiler, a coefficient of performance of 1.4 to 1.6 is achieved at a source temperature of 0°C (equal to a brine temperature of –3°C) and a supply temperature of 53°C of the heating system (Schirp 1996, Stahlberg and Wolf 2001, Jakob et al. 2003).

A seasonal performance factor (SPF) of 1.32 is used for the unit operated with a small-borehole heat exchanger and a supply temperature of 50- 60°C. For each MJ of supplied heat, only 0.758 MJ of fuel input is needed. The difference to the output of 1 MJ is accounted as “energy, geothermal, converted”.

7.5.2 Equipment needed

The infrastructure size needed is defined by the total operating life of the unit. Field test units achieve 40’000 hours of full-load operation (Stahlberg and Wolf, 2001). A heating system for residential use usually operates for about 2’000-2’500 hours per year of full load. A typical operating life of 15-20 years such as that for gas boilers will therefore be possible. An operating life of 42’000 hours of full-load operation (20 years at 2’100 h/y) similar to that of the gas boilers described by Faist Emmenegger et al. (2003) is used here. With a maximum heat output of 11 kW (including the integrated peak-load boiler), the operating life of the system is equivalent to 1.66 TJ of heat output, in other words $6.01*10^{-7}$ units are required per MJ of output.

A 40 m deep-borehole heat exchanger is used. Its infrastructure is modelled with the process described in Heck (2004) for a 150 m borehole heat exchanger with an operating life of 50 years. Due to the shorter borehole only 27% of this infrastructure process is used. This leads to an operating life equivalent to 4.16 TJ of heat output or an infrastructure demand of $6.41*10^{-8}$ units per MJ of output (50 years at 2’100 h/y).

7.5.3 Use of energy and auxiliaries

Natural gas consumption

The technical characteristics described in Section 7.5.1 are based on natural gas from the Swiss low-pressure gas network. Faist Emmenegger et al. (2003) show that this gas has a lower heating value (LHV) of 36.5 MJ/Nm^3 and a higher heating value (HHV) of 40.2 MJ/Nm^3. Due to the performance factor of 1.32 for each MJ of supplied heat, only 0.758 MJ of fuel input is needed.

Electricity consumption

No data are available for the total electricity consumption of the unit. Because it does not need a pump for the absorption circuit, the electricity is required mainly by the auxiliary systems such as the gas burner and the water circuit pump for the heat source circuit. The electricity requirement of the additional components is reported to be 1.2 kWh per 24 hours (Schirp, 1996), which is about 1% of the heat output. Faist Emmenegger et al. (2003) give the electricity consumption of small modulating gas boilers as 1% of the input. Electricity consumption of 2% of the heat output is used here.

7.5.4 Emissions to air

No information is available on the emissions of the diffusion-absorption heat pump. Because it operates very similarly to a condensing gas boiler, the emission values of a condensing, modulating gas boiler < 100kW are used here. Due to the fuel input of 0.758 MJ, the calculations are based on only 76% of the values per MJ of input presented in Faist Emmenegger et al. (2003).

7.5.5 Data quality considerations

Table 7.1 shows the unit process raw data and data-quality indicators of the inventory of heat, natural gas, at diffusion absorption heat pump 4 kW, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data obtained from a study of the literature and measurements for gas boilers. Although the inventory is partly based on measurements for gas boilers, it merely represents information available from the literature or from field test units.

Because these systems have so far been operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached by a series-manufactured product.

Table 7.1 Unit process raw data of heat, natural gas, at diffusion absorption heat pump 4 kW, future

	Name	Location	InfrastructureProcess	Unit	heat, natural gas, at diffusion absorption heat pump 4kW, future	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				MJ			
product	heat, natural gas, at diffusion absorption heat pump 4kW, future	CH	0	MJ	1			
technosphere	natural gas, low pressure, at consumer	CH	0	MJ	7.58E-1	1	1.26	(3,4,2,2,1,5); uncertainty of operation temperatures of source and supply
	electricity, low voltage, at grid	CH	0	kWh	5.56E-3	1	1.68	(4,5,2,2,4,5); estimate based on gas boiler data
	diffusion absorption heat pump 4kW, future	CH	1	unit	6.01E-7	1	1.32	(4,4,2,2,1,5); uncertainty of life time
	borehole heat exchanger 150 m	CH	1	unit	6.41E-8	1	3.10	(4,4,2,2,1,5); uncertainty of life time
resource, in ground	Energy, geothermal, converted	-	-	MJ	2.42E-1	1	1.26	(3,4,2,2,1,5); uncertainty of operation temperatures of source and supply
emission air, high population density	Heat, waste	-	-	MJ	1.10E+0	1	1.26	(3,4,2,2,1,5); uncertainty of operation temperatures of source and supply
	Acetaldehyde	-	-	kg	7.58E-10	1	8.00	rough estimate based on gas boiler data
	Benzo(a)pyrene	-	-	kg	7.58E-12	1	8.00	rough estimate based on gas boiler data
	Benzene	-	-	kg	3.03E-7	1	8.00	rough estimate based on gas boiler data
	Butane	-	-	kg	5.30E-7	1	8.00	rough estimate based on gas boiler data
	Methane, fossil	-	-	kg	1.52E-6	1	8.00	rough estimate based on gas boiler data
	Carbon monoxide, fossil	-	-	kg	4.47E-6	1	7.40	rough estimate based on calculation for gas boiler
	Carbon dioxide, fossil	-	-	kg	4.24E-2	1	1.10	based on composition of natural gas
	Acetic acid	-	-	kg	1.14E-7	1	8.00	rough estimate based on gas boiler data
	Formaldehyde	-	-	kg	7.58E-8	1	8.00	rough estimate based on gas boiler data
	Mercury	-	-	kg	2.27E-11	1	5.00	rough estimate based on gas boiler data
	Dinitrogen monoxide	-	-	kg	3.79E-7	1	8.00	rough estimate based on gas boiler data
	Nitrogen oxides	-	-	kg	7.50E-6	1	3.60	rough estimate based on calculation for gas boiler
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	7.58E-9	1	8.00	rough estimate based on gas boiler data
	Particulates, < 2.5 um	-	-	kg	7.58E-8	1	2.00	rough estimate based on gas boiler data
	Pentane	-	-	kg	9.09E-7	1	8.00	rough estimate based on gas boiler data
	Propane	-	-	kg	1.52E-7	1	8.00	rough estimate based on gas boiler data
	Propionic acid	-	-	kg	1.52E-8	1	8.00	rough estimate based on gas boiler data
	Sulfur dioxide	-	-	kg	3.79E-7	1	1.10	based on composition of natural gas
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	2.27E-17	1	8.00	rough estimate based on gas boiler data
	Toluene	-	-	kg	1.52E-7	1	8.00	rough estimate based on gas boiler data
emission water, river	Nitrate	-	-	kg	9.85E-8	1	3.00	rough estimate based on gas boiler data
	Nitrite	-	-	kg	2.27E-9	1	3.00	rough estimate based on gas boiler data
	Sulfate	-	-	kg	3.79E-8	1	3.00	rough estimate based on gas boiler data
	Sulfite	-	-	kg	3.79E-8	1	3.00	rough estimate based on gas boiler data

7.6 Heat, biogas, at diffusion absorption heat pump 4 kW

7.6.1 Technical characteristics

Only biogas distributed via the regular natural-gas network is considered for the operation of the diffusion-absorption heat pump system. Its quality is similar to that of natural gas. The content of methane must be at least 96% by volume.

Under these conditions, the operation of the system with biogas will be similar to that with natural gas (see Section 7.5.1). A system performance factor (SPF= 1.32) identical to that for operation with natural gas is used for the operation of the diffusion-absorption heat pump system with refined biogas.

7.6.2 Equipment needed

The infrastructure needed is similar to the values presented in Section 7.5.2 for operation with natural gas. Each MJ of supplied heat requires 0.758 MJ of fuel input. With a maximum heat output of 11 kW (including the integrated peak-load boiler), the operating life of the system is equivalent to 1.66 TJ of heat output, in other words $6.01*10^{-7}$ units per MJ of output are required. The borehole heat exchanger uses $6.41*10^{-8}$ units per MJ of output.

7.6.3 Energy and auxiliaries usage

Biogas consumption

The distribution requirements (energy, leakages) are similar to those for natural gas. The composition of the emissions differs only because of the different compositions of biogas and natural gas. The dataset “methane, 96 vol-%, from biogas, low pressure, at consumer” is used as the process input for the diffusion-absorption heat pump system. According to Jungbluth et al. (2007), the gas has a lower heating value of 34.45 MJ/Nm^3 and a higher heating value of 38.15 MJ/Nm^3. The performance factor of 1.32 per MJ of supplied heat means that 0.758 MJ of fuel input is needed.

Electricity consumption

An electricity consumption of 2% of the heat output is recorded (see Section 7.5.3).

7.6.4 Emissions to air

No information is available about the emissions of the diffusion-absorption heat pump. Because it operates very similarly to a condensing gas boiler, the emission values of a condensing modulating gas boiler < 100kW are used for this inventory. Due to the fuel input of 0.758 MJ, the calculations are based on only 76% of the values per MJ of input presented in Faist Emmenegger et al. (2003).

The CO_2 emissions are calculated on the basis of the carbon content of the biogas mix. The value of 42.3 g per MJ of heat output is calculated thereof excluding the carbon emitted in the form of CO, CH_4 and NMVOC.

7.6.5 Data quality considerations

Table 7.2 shows the unit process raw data and data-quality indicators of the inventory of heat, biogas, at diffusion absorption heat pump 4 kW, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data obtained from a study of the literature and measurements for gas boilers. Although the inventory is partly based on measurements for gas boilers, it merely represents information available from the literature or from field test units.

Because these systems have so far been operated only under test conditions, the performance data are based on the target values (efficiency) or approximations (emissions) expected to be reached by a series-manufactured product.

Table 7.2 Unit process raw data of heat, biogas, at diffusion absorption heat pump 4 kW, future

	Name	Location	InfrastructureProcess	Unit	heat, biogas, at diffusion absorption heat pump 4kW, future	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				MJ			
product	heat, biogas, at diffusion absorption heat pump 4kW, future	CH	0	MJ	1			
technosphere	methane, 96 vol-%, from biogas, low pressure, at consumer	CH	0	MJ	7.58E-1	1	1.26	(3,4,2,2,1,5); uncertainty of operation temperatures of source and supply
	electricity, low voltage, at grid	CH	0	kWh	5.56E-3	1	1.68	(4,5,2,2,4,5); estimate based on gas boiler data
	diffusion absorption heat pump 4kW, future	CH	1	unit	6.01E-7	1	1.32	(4,4,2,2,1,5); uncertainty of life time
	borehole heat exchanger 150 m	CH	1	unit	6.41E-8	1	3.10	(4,4,2,2,1,5); uncertainty of life time
resource, in ground	Energy, geothermal, converted	-	-	MJ	2.42E-1	1	1.26	(3,4,2,2,1,5); uncertainty of operation supply energy and heating value
emission air, high population density	Heat, waste	-	-	MJ	1.10E+0	1	1.26	(3,4,2,2,1,5); uncertainty of operation supply energy and heating value
	Acetaldehyde	-	-	kg	7.58E-10	1	8.00	rough estimate based on gas boiler data
	Benzo(a)pyrene	-	-	kg	7.58E-12	1	8.00	rough estimate based on gas boiler data
	Benzene	-	-	kg	3.03E-7	1	8.00	rough estimate based on gas boiler data
	Butane	-	-	kg	5.30E-7	1	8.00	rough estimate based on gas boiler data
	Methane, biogenic	-	-	kg	1.52E-6	1	8.00	rough estimate based on gas boiler data
	Carbon monoxide, biogenic	-	-	kg	4.47E-6	1	7.40	rough estimate based on calculation for gas boiler
	Carbon dioxide, biogenic	-	-	kg	4.23E-2	1	1.10	based on composition of refined biogas
	Acetic acid	-	-	kg	1.14E-7	1	8.00	rough estimate based on gas boiler data
	Formaldehyde	-	-	kg	7.58E-8	1	8.00	rough estimate based on gas boiler data
	Mercury	-	-	kg	2.27E-11	1	5.00	rough estimate based on gas boiler data
	Dinitrogen monoxide	-	-	kg	3.79E-7	1	8.00	rough estimate based on gas boiler data
	Nitrogen oxides	-	-	kg	7.50E-6	1	3.60	rough estimate based on calculation for gas boiler
	PAH, polycyclic aromatic hydrocarbons	-	-	kg	7.58E-9	1	8.00	rough estimate based on gas boiler data
	Particulates, < 2.5 um	-	-	kg	7.58E-8	1	2.00	rough estimate based on gas boiler data
	Pentane	-	-	kg	9.09E-7	1	8.00	rough estimate based on gas boiler data
	Propane	-	-	kg	1.52E-7	1	8.00	rough estimate based on gas boiler data
	Propionic acid	-	-	kg	1.52E-8	1	8.00	rough estimate based on gas boiler data
	Sulfur dioxide	-	-	kg	3.79E-7	1	1.10	based on composition of refined biogas
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	kg	2.27E-17	1	8.00	based on composition of refined biogas
	Toluene	-	-	kg	1.52E-7	1	8.00	rough estimate based on gas boiler data
emission water, river	Nitrate	-	-	kg	9.85E-8	1	3.00	rough estimate based on gas boiler data
	Nitrite	-	-	kg	2.27E-9	1	3.00	rough estimate based on gas boiler data
	Sulfate	-	-	kg	3.79E-8	1	3.00	rough estimate based on gas boiler data
	Sulfite	-	-	kg	3.79E-8	1	3.00	rough estimate based on gas boiler data

7.7 Manufacture of a Diffusion-absorption heat pump 4 kW

7.7.1 Technical characteristics

The infrastructure module for the 4 kW_{th} diffusion-absorption heat pump system includes the most important materials used for its production, the transport of these materials and the energy needed for production and engineering. The production process involves various steps, including raw material cutting, machining and welding. The main materials used are steel as well as stainless steel, aluminium, copper and liquids (ammonia) or gases (helium) for the absorption circuit. The total weight of the unit including the peak-load boiler is 250 kg (VSG 2006). It is assumed that the heat pump is produced in central Europe and is installed in Switzerland (planning and engineering in Switzerland).

7.7.2 Manufacturing site

No data are available for the production infrastructure of diffusion-absorption heat pump systems. It may be approximated by that of a production facility for similar products (Viessmann 2005). This production site has 35300 m^2 of floor space (offices, production and storage). A production output of 40000 units per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105900 m^3. The service life of the buildings is assumed to be 50 years. Each unit carries the environmental burden of 0.0089 m^2 of the building hall and 0.053 m^3 of the multi-storey building. All other infrastructures are neglected.

The land use of the production facilities is approximated on the basis of a similar production site (Viessmann 2005). An area of 63500 m^2 of this site is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). The service life of the buildings (50 years) is used for the occupation. Each unit carries the environmental burden of 0.032 m^2 of land transformation and 1.6 m^2 of land occupation.

7.7.3 Raw materials, energy and auxiliaries

Only rough information is available on the various components. The material balance presented in Tab. 7.3 is estimated on the basis of data from various sources (Schirp 1996, Stahlberg and Wolf 2001, Jakob et al. 2003). Missing data are estimated on the basis of gas boiler systems.

An additional energy requirement of 950 MJ for heat (natural gas, at industrial furnace >100kW) and 133 kWh electricity (medium voltage, production UCTE, at grid) is included for heating and electricity on the production site. The amount used is based on the specific energy requirement per kg of product of a similar production site (Viessmann 2005).

No data are available for the water consumed in manufacturing a diffusion-absorption heat pump system. A figure of 0.305m^3 is used here: this is based on the specific water demand of 1.22 litre per kg of product of a similar production site (Viessmann 2005).

Transportation of the raw materials is modelled by applying the standard distances for Europe according to (Frischknecht et al., 2004).

Additional energy is consumed for planning and engineering. Experience from similar projects suggests that 20 working hours of planning and engineering are needed for the heat pump unit. On the basis of data from Aebischer and Catenazzi (2006), a specific energy consumption of 15 MJ/h of heat (light fuel oil burned in a 100 kW non-modulating boiler) and 2 kWh/h of electricity (low voltage, at grid, CH) is used to calculate the energy requirement. Moreover, it is assumed that the construction site is visited once and the distance of 200 km (return trip) for the visit is covered by car.

7.7.4 Emissions to air and water

Emissions to air are included in the unit processes used (e.g. heating or transport processes). No further process-related emissions occur. For the waste water disposal an average wastewater treatment process is used due to lack of data on water emissions from manufacturing. It is assumed that all fresh water used is disposed as waste water to a wastewater treatment plant.

7.7.5 Dismantling

After its service life, the diffusion-absorption heat pump system is dismantled and the materials recycled or disposed of. It is assumed that all metals (224 kg) will be recycled. No environmental burdens from dismantling and recycling are included (cut-off) for these materials. Final disposal in a municipal incineration plant is assumed for plastic materials (8 kg). The rock wool used as insulation (8 kg) is landfilled and for the electronic parts (4 kg) the disposal process "disposal, electronics for control units" is used.

7.7.6 Data quality considerations

Tab. 7.3 shows the unit process raw data and data-quality indicators of the manufacture of a diffusion absorption heat pump 4 kW, future.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for additional processes and materials which are not covered in the data source. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 7.3 Unit process raw data of the manufacture of a diffusion absorption heat pump 4 kW, future

	Name	Location	InfrastructureProcess	Unit	diffusion absorption heat pump 4kW, future	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	diffusion absorption heat pump 4kW, future	CH	1	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	1.65E+2	1	1.34	(4,4,3,2,1,5); estimation based on few references
	chromium steel 18/8, at plant	RER	0	kg	3.20E+1	1	1.34	(4,4,3,2,1,5); estimation based on few references
	aluminium, production mix, wrought alloy, at plant	RER	0	kg	2.20E+1	1	1.34	(4,4,3,2,1,5); estimation based on few references
	copper, at regional storage	RER	0	kg	5.00E+0	1	1.34	(4,4,3,2,1,5); estimation based on few references
	rock wool, packed, at plant	CH	0	kg	8.00E+0	1	1.34	(4,4,3,2,1,5); estimation for insulation based on few references
	polyethylene, HDPE, granulate, at plant	RER	0	kg	4.00E+0	1	1.34	(4,4,3,2,1,5); estimation for plastic material based on few references
	tube insulation, elastomere, at plant	DE	0	kg	4.00E+0	1	1.34	(4,4,3,2,1,5); estimation based on few references
	electronics for control units	RER	0	kg	4.00E+0	1	1.34	(4,4,3,2,1,5); estimation for control electronic based on few references
	ammonia, liquid, at regional storehouse	CH	0	kg	1.50E+0	1	1.34	(4,4,3,2,1,5); estimation based on few references
	helium, gaseous, at plant	RER	0	kg	1.00E-1	1	1.40	(4,5,3,2,1,5); rough estimation
	water, completely softened, at plant	RER	0	kg	5.00E+0	1	1.34	(4,4,3,2,1,5); estimation based on few references
	sheet rolling, steel	RER	0	kg	1.65E+2	1	1.34	(4,4,3,2,1,5); based on material input
	sheet rolling, chromium steel	RER	0	kg	3.20E+1	1	1.34	(4,4,3,2,1,5); based on material input
	injection moulding	RER	0	kg	4.00E+0	1	1.34	(4,4,3,2,1,5); based on material input
	zinc coating, coils	RER	0	m2	1.50E+1	1	1.34	(4,4,3,2,1,5); based on material input
	transport, freight, rail	RER	0	tkm	4.97E+1	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	7.47E+1	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, passenger car	CH	0	pkm	2.00E+2	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	9.50E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	3.00E+2	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.33E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	electricity, low voltage, at grid	CH	0	kWh	4.00E+1	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	8.00E+0	1	1.34	(4,4,3,2,1,5); disposal of plastic material
	disposal, building, mineral wool, to final disposal	CH	0	kg	8.00E+0	1	1.34	(4,4,3,2,1,5); disposal of insulation material
	disposal, electronics for control units	RER	0	kg	4.00E+0	1	1.34	(4,4,3,2,1,5); disposal of electronic parts material
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	3.05E-1	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	5.30E-2	1	3.12	(4,4,2,5,1,5); rough estimation based on company data of similar branch
	building, hall, steel construction	CH	1	m2	8.90E-3	1	3.12	(4,4,2,5,1,5); rough estimation based on company data of similar branch
resource, in water	Water, unspecified natural origin	-	-	m3	3.05E-1	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	1.60E+0	1	1.65	(4,4,2,5,1,5); rough estimation based on company data of similar branch
	Transformation, from unknown	-	-	m2	3.20E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data of similar branch
	Transformation, to industrial area, built up	-	-	m2	3.20E-2	1	2.12	(4,4,2,5,1,5); rough estimation based on company data of similar branch
emission air, high population density	Heat, waste	-	-	MJ	6.23E+2	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

7.8 Cooling energy, natural gas, at cogen unit with absorption chiller 100 kW

7.8.1 Technical characteristics

Depending on the heat source and the temperature of the chilled water the technical characteristics of a cooling system with an absorption chiller is very different. Especially the coefficient of performance (COP) and the seasonal performance factor (SPF) vary largely. The cooling system analysed here operates with a single-stage absorption chiller, a heat source of 85-100°C and a chilled water temperature of 6°C.

Coefficient of performance

A single-stage LiBr-H_2O absorption chiller has a coefficient of performance (COP) of approximately 0.65 to 0.70 when operated with 100°C steam (or hot water) entering the generator, 30°C cooling water, and 6°C leaving chilled water (Soo et al., 1997). A COP of 0.55 to 0.70 is expected for usual temperature levels in co-generation systems. Single-stage water/ammonia absorption chillers have a reduced COP (0.45-0.6) under these operation conditions (Bine, 1998). Such units are suitable for cooling applications below 5°C. They are currently being developed for applications with solar collectors. Two-stage LiBr-H_2O absorption chillers have a significantly higher COP (up to 1.2). However, the temperature requirements for these systems are much higher (145-180°C), making them unsuitable for many co-generation applications. Fig. 7.3 shows the COP of a single-stage LiBr-H_2O absorption unit as a function of the temperature difference between the condenser (T_C, 25-45°C) and the evaporator (T_e, 2-12 °C), with 38°C at the absorber and 100 °C at the generator (Soo et al., 1997).

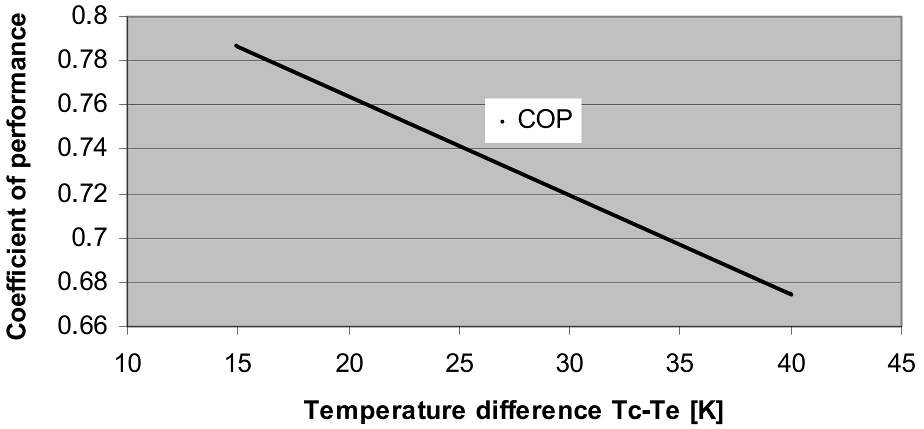

Fig. 7.3 **COP of a single-stage LiBr-H2O absorption unit as a function of the temperature difference between condenser and evaporator**

Seasonal performance factor

The seasonal performance factor (SPF) is the average coefficient of performance over a whole season of operation (usually one year). A seasonal performance factor of the system of 0.6 is assumed for the cooling system analysed here.

7.8.2 Equipment needed

The infrastructure needed is defined by the total operating life of the unit. A typical operating life of an absorption chiller is 15 years. A cooling system for office buildings usually operates for about 500-1’500 hours per year at full load. For industrial cooling applications much higher hours of full-load operation are possible. An operating life of 20’000 hours of full-load operation (20 years at 1’000 h/y) is used. With a maximum chilled water output of 100 kW the operating life of the system is equivalent to 7.2 TJ of chilled water output, in other words $1.39*10^{-7}$ units are required per MJ of output.

7.8.3 Use of energy and auxiliaries

Operation energy

For an absorption chiller with a seasonal performance factor (SPF) of 0.6 for every MJ of cooling energy, 1.67 MJ of heat is needed. For the heat production the process “heat, at cogen 160kWe lambda=1, allocation exergy” is used. Any other heat source with a temperature between 85 to 100°C may be used for this process.

Electricity consumption

The electricity needed for operation amounts to 60-80 kWh per MWh of chilled water output (Bine, 1998). A electricity consumption of 0.02 kWh per MJ of chilled water output is used.

Water use

For absorption chiller with a seasonal performance factor (SPF) of 0.6 for every MJ of cooling energy, 2.67 MJ of heat must be rejected at the cooling tower. The water use during operation of the absorption chiller unit is about 5-6 m^3 per MWh of chilled water output (Bine, 1998). This amount depends strongly on the cooler system used. A water use of 1.5 kg per MJ of chilled water output is used. The water used for the cooling tower has to be decarbonised.

7.8.4 Emissions to air

No information is available on the emissions of absorption chillers. Emissions to air are included in the unit processes used (heat, at cogen 160kWe lambda=1, allocation exergy). The water used for the cooling tower evaporates (not accounted as emission). No further process-related emissions occur.

7.8.5 Data quality considerations

Tab. 7.4 shows the unit process raw data and data-quality indicators of the inventory of cooling energy, natural gas, at cogen unit with absorption chiller 100 kW.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data obtained from a study of the literature and measurements for gas boilers. Although the inventory is partly based on measurements for gas boilers, it merely represents information available from the literature or from field test units.

Because these systems have so far been operated only under test conditions, the performance data are based on target values (efficiency) or approximations (emissions) which are expected to be reached by a series-manufactured product.

Tab. 7.4 Unit process raw data of cooling energy, natural gas, at cogen unit with absorption chiller 100 kW

	Name	Location	InfrastructureProce	Unit	cooling energy, natural gas, at cogen unit with absorption chiller 100 kW	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				0			
	Unit				MJ			
product	cooling energy, natural gas, at cogen unit with absorption	CH	0	MJ	1			
technosphere	absorption chiller 100kW	CH	1	unit	1.39E-7	1	1.32	(4,4,2,2,1,5); uncertainty of life time
	heat, at cogen 160kWe lambda=1, allocation exergy	CH	0	MJ	1.67E+0	1	1.26	(3,4,2,2,1,5); uncertainty of operation temperatures of source and supply
	electricity, low voltage, at grid	CH	0	kWh	2.00E-2	1	1.36	(3,4,3,2,3,5); data based on average process efficiency
	water, decarbonised, at plant	RER	0	kg	1.50E+0	1	1.36	(3,4,3,2,3,5); data based on average process efficiency
air, high population density	Heat, waste	-	-	MJ	7.20E-2	1	1.36	(3,4,3,2,3,5); uncertainty electricity demand

7.9 Manufacture of a Absorption chiller 100 kW

7.9.1 Technical characteristics

The infrastructure dataset representing the production of the 100 kW absorption chiller unit includes the most important materials used for its production, the transport of these materials and the energy needed for production. The production process involves various steps including raw material cutting, machining and welding. The main materials used are steel as well as stainless steel, copper, aluminium, and liquids (ammonia) for the absorption and cooling circuit. The total weight of the unit analysed (including hybrid cooler and piping) is 4900 kg. It is assumed that the heat pump is produced in central Europe and is installed in Switzerland (planning and engineering in Switzerland).

7.9.2 Manufacturing site

No data are available on the production infrastructure for an absorption chiller. The infrastructure size is approximated with reference to a production facility for conventional heating systems (Viessmann 2005). This production site has 35300 m^2 of floor space (offices, production and storage). A production output of 2000 units per year is assumed on the basis of the total annual production in kg of this plant. No detailed information is available on the buildings and other infrastructures. It is assumed that 17700 m^2 (50%) of the floor space is a building hall (steel construction) and the rest is a multi-storey building with a volume of 105900 m^3. The service life of the buildings is assumed to be 50 years. Each unit carries the environmental burden of 0.177 m^2 of the building hall and 1.06 m^3 of the multi-storey building. Further infrastructures are neglected.

The land use of the production facilities is approximated with reference to the data of a similar production site (Viessmann 2005). An area of 63500 m^2 of this site is sealed. This area is accounted as “industrial area, built up” (transformation from unknown). For the occupation, the service life of the buildings (50 years) is used. Each unit carries the environmental burden of 0.635 m^2 land transformation and 31.8 m^2 of land occupation.

7.9.3 Raw materials, energy and auxiliaries

Only rough information is available on the various components. The material balance is estimated on the basis of data from various manufacturers and the literature (Jäggi-Güntner 2004, Yazaki 2000, York 1999, York 1997, Beuchat et al. 2005, Kevin and Rafferty 1998). Missing data are estimated in order to reach the total weight of the unit. The 100 kW single-stage absorption chiller consists of a water/ammonia cycle with a 250 kW hybrid cooler and 40 m of piping to cover the distance between absorption chiller and air cooler (assumptions).

Each absorption chiller has an energy requirement of 18.7 GJ of heat (natural gas for an industrial furnace >100kW) and 2.6 MWh electricity (medium voltage, production UCTE, at grid). The amounts used are based on the specific energy requirement per kg product of a similar production site (Viessmann 2005).

No data are available on the water consumption required for manufacturing a diffusion-absorption heat pump system. A figure of 5.98 m^3 is used here: it is based on the specific water requirement of 1.22 litre per kg product of a similar production site (Viessmann 2005).

Transportation of the raw materials is modelled by applying the standard distances for Europe according to (Frischknecht et al., 2004).

Additional energy is consumed for planning and engineering. Experience from similar projects suggests that 400 working hours for planning and engineering wil be needed for the 100 kW absorption chiller. Data from Aebischer and Catenazzi (2006) suggests that a specific energy consumption of 15 MJ/h of heat (light fuel oil, burned in boiler 100kW, non-modulating) and 2 kWh/h of electricity (low voltage, at grid, at grid, CH) should be used to calculate the energy requirement. Moreover, it is assumed that the construction site is visited 10 times and the distance of 200 km (return trip) for the visit is covered by car.

7.9.4 Emissions to air and water

Emissions to air are included in the unit processes used (e.g. heating or transport processes). No further process-related emissions occur. For the waste water disposal an average wastewater treatment process is used due to lack of data on water emissions from manufacturing. It is assumed that all fresh water used is disposed as waste water to a wastewater treatment plant.

7.9.5 Dismantling

After its service life, the 100 kW absorption chiller system is dismantled and the materials are recycled or disposed of. It is assumed that all metals (224 kg) will be recycled. No environmental burdens from dismantling and recycling are included (cut-off) for these materials. Final disposal in a municipal incineration plant is assumed for plastic materials (8 kg). The rock wool used as insulation (8 kg) is landfilled and for the electronic parts (4 kg) the disposal process “disposal, electronics for control units” is used.

7.9.6 Data quality considerations

Tab. 7.5 shows the unit process raw data and data-quality indicators of the manufacture of a 100 kW absorption chiller.

A simplified approach with a pedigree matrix is used to calculate the standard deviation. However, the basic uncertainty has been adjusted to represent the ranges of the data obtained from a study of the literature. The inventory is based on only a few sources as well as on an estimate for additional processes and materials which are not covered in the data source. Large uncertainties exist for the transport distances and the energy requirement for manufacturing.

Tab. 7.5 Unit process raw data of the manufacture of a 100kW absorption chiller

	Name	Location	InfrastructureProce	Unit	absorption chiller 100kW	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				CH			
	InfrastructureProcess				1			
	Unit				unit			
product	absorption chiller 100kW	CH	1	unit	1			
technosphere	reinforcing steel, at plant	RER	0	kg	3.22E+3	1	1.41	(4,4,3,2,3,5); estimation based on few references
	chromium steel 18/8, at plant	RER	0	kg	4.80E+2	1	1.41	(4,4,3,2,3,5); estimation based on few references
	aluminium, production mix, wrought alloy, at plant	RER	0	kg	4.20E+2	1	1.41	(4,4,3,2,3,5); estimation based on few references
	copper, at regional storage	RER	0	kg	4.80E+2	1	1.41	(4,4,3,2,3,5); estimation based on few references
	rock wool, packed, at plant	CH	0	kg	7.00E+1	1	1.41	(4,4,3,2,3,5); estimation for heat insulation
	polyethylene, HDPE, granulate, at plant	RER	0	kg	4.00E+1	1	1.41	(4,4,3,2,3,5); estimation for plastic material based on few references
	tube insulation, elastomere, at plant	DE	0	kg	9.00E+1	1	1.41	(4,4,3,2,3,5); estimation based on few references
	electronics for control units	RER	0	kg	6.00E+1	1	1.41	(4,4,3,2,3,5); estimation for control electronic based on few references
	ammonia, liquid, at regional storehouse	CH	0	kg	7.20E+1	1	1.41	(4,4,3,2,3,5); estimation based on few references
	ethylene glycol, at plant	RER	0	kg	1.50E+2	1	1.41	(4,4,3,2,3,5); estimation based on few references
	water, completely softened, at plant	RER	0	kg	6.30E+2	1	1.41	(4,4,3,2,3,5); estimation based on few references
	sheet rolling, steel	RER	0	kg	3.22E+3	1	1.41	(4,4,3,2,3,5); based on material input
	sheet rolling, chromium steel	RER	0	kg	4.80E+2	1	1.41	(4,4,3,2,3,5); based on material input
	sheet rolling, aluminium	RER	0	kg	4.20E+2	1	1.41	(4,4,3,2,3,5); based on material input
	wire drawing, copper	RER	0	kg	4.80E+2	1	1.41	(4,4,3,2,3,5); based on material input
	injection moulding	RER	0	kg	4.00E+1	1	1.41	(4,4,3,2,3,5); based on material input
	zinc coating, coils	RER	0	m2	6.80E+1	1	1.41	(4,4,3,2,3,5); based on material input
	transport, freight, rail	RER	0	tkm	1.05E+3	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, lorry >16t, fleet average	RER	0	tkm	1.49E+3	1	2.09	(4,5,nA,nA,nA,nA); standard distances used
	transport, passenger car	CH	0	pkm	2.00E+3	1	2.16	(4,4,2,1,3,5); estimation
	natural gas, burned in industrial furnace >100kW	RER	0	MJ	9.50E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	light fuel oil, burned in boiler 100kW, non-modulating	CH	0	MJ	6.00E+3	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	1.33E+2	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
	electricity, low voltage, at grid	CH	0	kWh	8.00E+2	1	1.29	(3,4,2,1,3,4); estimation based on specific energy demand of engineering hours
	disposal, building, polyethylene/polypropylene products, to final disposal	CH	0	kg	1.30E+2	1	1.41	(4,4,3,2,3,5); disposal of plastic material
	disposal, electronics for control units	RER	0	kg	6.00E+1	1	1.41	(4,4,3,2,3,5); disposal of electronic parts material
	disposal, building, mineral wool, to final disposal	CH	0	kg	7.00E+1	1	1.41	(4,4,3,2,3,5); disposal of heat insulation material
	treatment, heat carrier liquid, 40% C3H8O2, to wastewater treatment, class 2	CH	0	m3	3.75E-1	1	1.41	(4,4,3,2,3,5); disposal of insulation material
	treatment, sewage, from residence, to wastewater treatment, class 2	CH	0	m3	5.98E+0	1	1.64	(4,4,1,2,4,5); approximation for waste water treatment
	building, multi-storey	RER	1	m3	1.06E+0	1	3.16	(4,4,2,5,3,5); rough estimation based on company data of similar branch
	building, hall, steel construction	CH	1	m2	1.77E-1	1	3.16	(4,4,2,5,3,5); rough estimation based on company data of similar branch
resource, in water	Water, unspecified natural origin	-	-	m3	5.98E+0	1	1.58	(2,4,1,2,4,5); approximation with company data of similar branch
resource, land	Occupation, industrial area	-	-	m2a	3.18E+1	1	1.70	(4,4,2,5,3,5); rough estimation based on company data of similar branch
	Transformation, from unknown	-	-	m2	6.35E-1	1	2.17	(4,4,2,5,3,5); rough estimation based on company data of similar branch
	Transformation, to industrial area, built up	-	-	m2	6.35E-1	1	2.17	(4,4,2,5,3,5); rough estimation based on company data of similar branch
emission air, high population density	Heat, waste	-	-	MJ	3.36E+3	1	1.58	(2,4,1,2,4,5); uncertainty electricity demand

7.10 Cumulative results and interpretation

7.10.1 Introduction

Selected LCI results and values for the cumulative energy requirement are presented and discussed in this section. Please note that only a small part of the 1500 elementary flows is presented here. The selection of the elementary flows shown in the tables is not based on their environmental relevance. Rather, it allows the contributions of the different life cycle phases or specific inputs from the technosphere to the selected elementary flows to be illustrated. Please refer to the *ecoinvent* database for the complete LCIs.

The selection shown is unsuitable for a life-cycle assessment of the analysed processes and products. Please download data from the database for your own calculations, not least because of possible minor deviations between the presented results and the database due to corrections and changes made in the background data used as inputs to the relevant dataset.

The *ecoinvent* database also contains the results of life-cycle impact assessments. Assumptions and interpretations are necessary to match current LCIA methods to the *ecoinvent* inventory results. They are described in Frischknecht et al. (2007). You are strongly advised to read the respective sections of the implementation report before applying the LCIA results.

Process “heat, natural gas, at diffusion absorption heat pump 4 kW, future”

The major part of the NMVOC (97%), nitrogen oxide (62%) and particulate < 2.5um emissions (41%) and the cumulative energy demand (fossil: 98%, nuclear: 90%) are caused by the natural gas used for operation. The major part of the carbon dioxide (85%) emissions are caused by direct emissions from operation. Also a smaller part of the nitrogen oxide (25%) and particulate < 2.5um emissions (5%) are caused by direct emissions from operation. The heat pump infrastructure is for the particulate < 2.5um emissions (49%) of importance. Tab. 7.6 shows selected LCI results and cumulative energy demands for heat production with a diffusion absorption heat pump.

Process “heat, biogas, at diffusion absorption heat pump 4 kW, future”

The major part of the fossil carbon dioxide (88%), NMVOC (82%), nitrogen oxide (45%) and particulate < 2.5um emissions (49%) and the cumulative energy demand (biomass: 71%, fossil: 89%, nuclear: 75%) are caused by the refined biogas used for operation. A smaller part of the nitrogen oxide (35%) and particulate < 2.5um emissions (5%) are caused by direct emissions from operation. The heat pump infrastructure is for the particulate < 2.5um emissions (29%) of importance. Tab. 7.6 shows selected LCI results and cumulative energy demands for heat production with a diffusion absorption heat pump.

Process “diffusion absorption heat pump 4 kW, future”

The major part of the fossile carbon dioxide (50%), NMVOC (40%), nitrogen oxide (50%) and particulate < 2.5um emissions (71%) and the cumulative energy demand (fossil: 50%, nuclear: 42%) are caused by the steel, stainless steel and aluminium used. For the NMVOC emissions (17%) and the cumulative nuclear energy demand (13%) the electronic components are of importance. Tab. 7.6 shows selected LCI results and cumulative energy demands for the manufacture of a diffusion absorption heat pump.

Process “cooling energy, natural gas, at cogen unit with absorption chiller 100 kW”

The major part of the carbon dioxide (90%), NMVOC (91%), nitrogen oxide (72%) and particulate < 2.5um emissions (64%) and the cumulative fossil energy demand (92%) are caused by the heat used for the operation of the absorption chiller. The major part of the cumulative nuclear energy demand (93%) are caused by the electricity demand for the operation of the absorption chiller. The manufacturing of the absorption chiller is for the cadmium soil emissions (83%) of large importance. Tab. 7.6 shows selected LCI results and cumulative energy demands for heat production with a diffusion absorption heat pump.

Process “100kW absorption chiller”

The major part of the fossil carbon dioxide (54%), NMVOC (38%), nitrogen oxide (45%) and particulate < 2.5um emissions (54%) and the cumulative energy demand (fossil: 53%, nuclear: 43%) are caused by the steel, stainless steel and aluminium used. For the NMVOC air emissions (14%), cadmium soil emissions (94%) and the cumulative nuclear energy demand (11%) the electronic components are of importance. Tab. 7.6 shows selected LCI results and cumulative energy demands for the manufacture of a 100kW absorption chiller.

Tab. 7.6 Selected LCI results and the cumulative energy demand for a 4kW diffusion absorption heat pump

Ecocat	Ecosubcat	Name	Name	heat, natural gas, at diffusion absorption heat pump 4kW, future	heat, biogas, at diffusion absorption heat pump 4kW, future	diffusion absorption heat pump 4kW, future	cooling energy, natural gas, at cogen unit with absorption chiller 100 kW	absorption chiller 100kW
			Location Unit	CH MJ	CH MJ	CH unit	CH MJ	CH unit
cumulative energy demand	fossil	non-renewable energy resources, fossil	MJ-Eq	9.32E-01	2.04E-01	1.62E+04	9.18E-01	2.73E+05
	nuclear	non-renewable energy resources, nuclear	MJ-Eq	4.54E-02	1.78E-01	3.65E+03	1.60E-01	6.40E+04
	primary forest	non-renewable energy resources, primary forest	MJ-Eq	1.22E-06	6.77E-07	2.85E-02	1.21E-06	5.27E-01
	water	renewable energy resources, water	MJ-Eq	1.05E-02	3.75E-02	1.30E+03	3.55E-02	2.42E+04
	biomass	renewable energy resources, biomass	MJ-Eq	6.38E-04	1.47E-03	2.25E+02	1.85E-03	3.97E+03
	wind	renewable energy resources, kinetic (in wind), converted	MJ-Eq	1.95E-04	5.99E-04	4.92E+01	6.38E-04	8.51E+02
	geothermal	renewable energy resources, geothermal, converted	MJ-Eq	2.42E-01	2.42E-01	0.00E+00	0.00E+00	0.00E+00
	solar	renewable energy resources, solar, converted	MJ-Eq	5.31E-06	1.95E-05	7.34E-01	1.85E-05	1.28E+01
selected LCI results	resource	land occupation	m2a	1.38E-04	3.11E-04	6.06E+01	3.83E-04	1.36E+03
	air	CO2, fossil	kg	4.98E-02	1.22E-02	1.12E+03	5.02E-02	1.92E+04
	air	NMVOC	kg	3.18E-05	7.82E-06	7.26E-01	3.09E-05	1.37E+01
	air	nitrogen oxides	kg	3.05E-05	2.13E-05	2.57E+00	4.00E-05	5.07E+01
	air	sulphur dioxide	kg	2.60E-05	2.50E-05	4.01E+00	4.56E-05	1.08E+02
	air	particulates, <2.5 um	kg	1.38E-06	1.58E-06	7.67E-01	3.74E-06	1.71E+01
	water	BOD	kg	7.33E-06	6.17E-06	2.51E+00	1.50E-05	5.91E+01
	soil	cadmium	kg	3.15E-12	4.43E-12	4.13E-06	1.05E-11	6.26E-05

7.11 Conclusions

The LCI results show that the fuel and the emissions from the operation are for many elementary flows the main impact. But especially for elementary flows important for toxicity (e.g. cadmium soil emissions in Tab. 7.6) the production of the infrastructure is of high importance.

A reduction of the cumulative fossil energy demand, the fossil carbon dioxide and NMVOC emissions to 20-25% are achieved by the use of biogas (refined biogas distributed via the regular natural-gas network) instead of natural gas. On the other hand the cumulative energy demand for nuclear energy and biomass and the land use are by a factor 2 to 4 higher with the use of biogas.

7.12 Appendices: EcoSpold Meta Information

Tab. 7.7 EcoSpold Meta Information of a 4 kW diffusion absorption heat pump and a 100 kW absorption chiller

ReferenceFunction	Name	diffusion absorption heat pump 4kW, future	heat, biogas, at diffusion absorption heat pump 4kW, future	heat, natural gas, at diffusion absorption heat pump 4kW, future	absorption chiller 100kW	cooling energy, natural gas, at cogen unit with absorption chiller 100 kW
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctic	InfrastructureProcess	1	0	0	1	0
ReferenceFunctic	Unit	unit	MJ	MJ	unit	MJ
DataSetInformatic	Type	1	1	1	1	1
	Version	2.0	2.0	2.0	2.0	2.0
	energyValues	0	0	0	0	0
	LanguageCode	en	en	en	en	en
	LocalLanguageCode	de	de	de	de	de
DataEntryBy	Person	72	72	72	72	72
	QualityNetwork	1	1	1	1	1
ReferenceFunctic	DataSetRelatesToProduct	1	1	1	1	1
	IncludedProcesses	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials.	The module includes input biogas input from low pressure gas network (CH), infrastructure (heat pump with peak boiler and borehole heat exchanger), emissions to air and water, and electricity needed for operation.	The module includes input natural gas input from low pressure gas network (CH), infrastructure (heat pump with peak boiler and borehole heat exchanger), emissions to air and water, and electricity needed for operation.	The module includes the most important materials used for production, the energy needed for production, planning and engineering. Also included is the transport of the raw materials.	The module includes heat input from a 160kWel cogeneration unit, electricity and water needed for operation and infrastructure (absorption chiller, air cooler, piping).
	Amount	1	1	1	1	1
	LocalName	Diffusions-Absorptions-Wärmepumpe 4kW, zukünftig	Nutzwärme, Biogas, ab Diffusions-Absorptions-Wärmepumpe 4kW, zukünftig	Nutzwärme, Erdgas, ab Diffusions-Absorptions-Wärmepumpe 4kW, zukünftig	Absorptionskältemaschine 100 kW	Kälte, Erdgas, ab BHKW mit Absorptionskältemaschine 100 kW
	Synonyms	DAHP//DAWP	DAHP//DAWP	DAHP//DAWP		
	GeneralComment	The module reflects a diffusion absorption heat pump with peak load gas-boiler and a short borehole heat exchanger. Inventory based on information from literature for future production based on manufacturer data. Life time for the total system assumed with 20 years or 42'000 h full load operation.	NOx and CO emissions derived from measurements of gas boilers operated with natural gas under controlled conditions; no adjustment to real operation of the heat pump system is made due to lack of information. Other emission approximised with data for gas boilers from different references.	NOx and CO emissions derived from measurements of gas boilers operated with natural gas under controlled conditions; no adjustment to real operation of the heat pump system is made due to lack of information. Other emission approximised with data for gas boilers from different references.	The module reflects a absorption chiller with 100kW coling capacity and a air cooler for the waste heat. Inventory based on information from literature for future production based on manufacturer data. Life time for the total system assumed with 20 years.	The module reflects an absorption chiller operated with heat from a natural gas operated cogeneration unit (allocation exergy). Life time for the total system assumed with 20 years or 20'000 full operating hours.
	InfrastructureIncluded	1	1	1	1	1
	Category	heat pumps	heat pumps	heat pumps	cooling	cooling
	SubCategory	production of components	heating systems	heating systems	production of components	cogeneration
	LocalCategory	Wärmepumpen	Wärmepumpen	Wärmepumpen	Kältetechnik	Kältetechnik
	LocalSubCategory	Herstellung Komponenten	Heizungssysteme	Heizungssysteme	Herstellung Komponenten	Wärmekraftkopplung (WKK)
	Formula					
	StatisticalClassification					
	CASNumber					
TimePeriod	StartDate	2000	2000	2000	2000	2000
	EndDate	2005	2005	2005	2005	2005
	DataValidForEntirePeriod	1	1	1	1	1
	OtherPeriodText					

Tab. 7.7 (Part 2) EcoSpold Meta Information of a 4 kW diffusion absorption heat pump and a 100 kW absorption chiller

ReferenceFunction	Name	diffusion absorption heat pump 4kW, future	heat, biogas, at diffusion absorption heat pump 4kW, future	heat, natural gas, at diffusion absorption heat pump 4kW, future	absorption chiller 100kW	cooling energy, natural gas, at cogen unit with absorption chiller 100 kW
Geography	Location	CH	CH	CH	CH	CH
ReferenceFunctio	InfrastructureProcess	1	0	0	1	0
ReferenceFunctio	Unit	unit	MJ	MJ	unit	MJ
Geography	Text	Process applicable in central European conditions.	Natural gas input modelled for Switzerland. Process applicable in central European conditions.	Biogas input modelled for conditions in Switzerland. Process applicable in central European conditions.	Process applicable in central European conditions.	Natural gas input for cogeneration unit and electricity demand modelled for Switzerland. Process applicable in central European conditions.
Technology	Text	Diffusion absorption heat pump with 4 kWth nominal thermal power connected to a short borehole heat exchanger. The unit includes a peak load boiler which allows a maximal output power of 11 kWth. Operation with connection to low pressure gas network. Seasonal performance factor (SPF) of 1.32. Supply temperature of the heating system 50°C.	Diffusion absorption heat pump with 4 kWth nominal thermal power connected to a short borehole heat exchanger. The unit includes a peak load boiler which allows a maximal output power of 11 kWth. Operation with connection to low pressure gas network. Seasonal performance factor (SPF) of 1.32. Supply temperature of the heating system 50°C.	Diffusion absorption heat pump with 4 kWth nominal thermal power connected to a short borehole heat exchanger. The unit includes a peak load boiler which allows a maximal output power of 11 kWth. Operation with connection to low pressure gas network. Seasonal performance factor (SPF) of 1.32. Supply temperature of the heating system 50°C.	Single stage absorption chiller with water-ammonia cycle and 100 kW cooling capacity connected to a 250 kW hybrid air cooler. The unit includes 40m of piping between the chiller and the air cooler. Coefficient of performance between 0.4 and 0.7 depending on supply temperatures.	Single stage absorption chiller with 100 kW cooling capacity connected to a 250 kW hybrid air cooler. Seasonal performance factor (SPF) of 0.6. Supply temperature of the chilled water 6°C. Operated with heat of a temperature of 85- 100°C.
Representativene	Percent					
	ProductionVolume	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	Literature data and manufacturer information	Literature data and manufacturer information, emissions values from ecoinvent process natural gas, burned in boiler condensing modulating under 100kW	Literature data and manufacturer information, emissions from ecoinvent process natural gas, burned in boiler condensing modulating under 100kW	Literature data and manufacturer information	Literature data and manufacturer information
	Extrapolations	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none
DataGeneratorAn	Person	72	72	72	72	72
	DataPublishedIn	2	2	2	2	2
	ReferenceToPublishedSource	47	47	47	47	47
	Copyright	1	1	1	1	1
	AccessRestrictedTo	0	0	0	0	0
	CompanyCode					
	CountryCode					
	PageNumbers	Absorption	Absorption	Absorption	Absorption	Absorption
ProofReading	Validator	42	42	42	42	42
	Details	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel	automatic validation in Excel
	OtherDetails	none	none	none	none	none

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