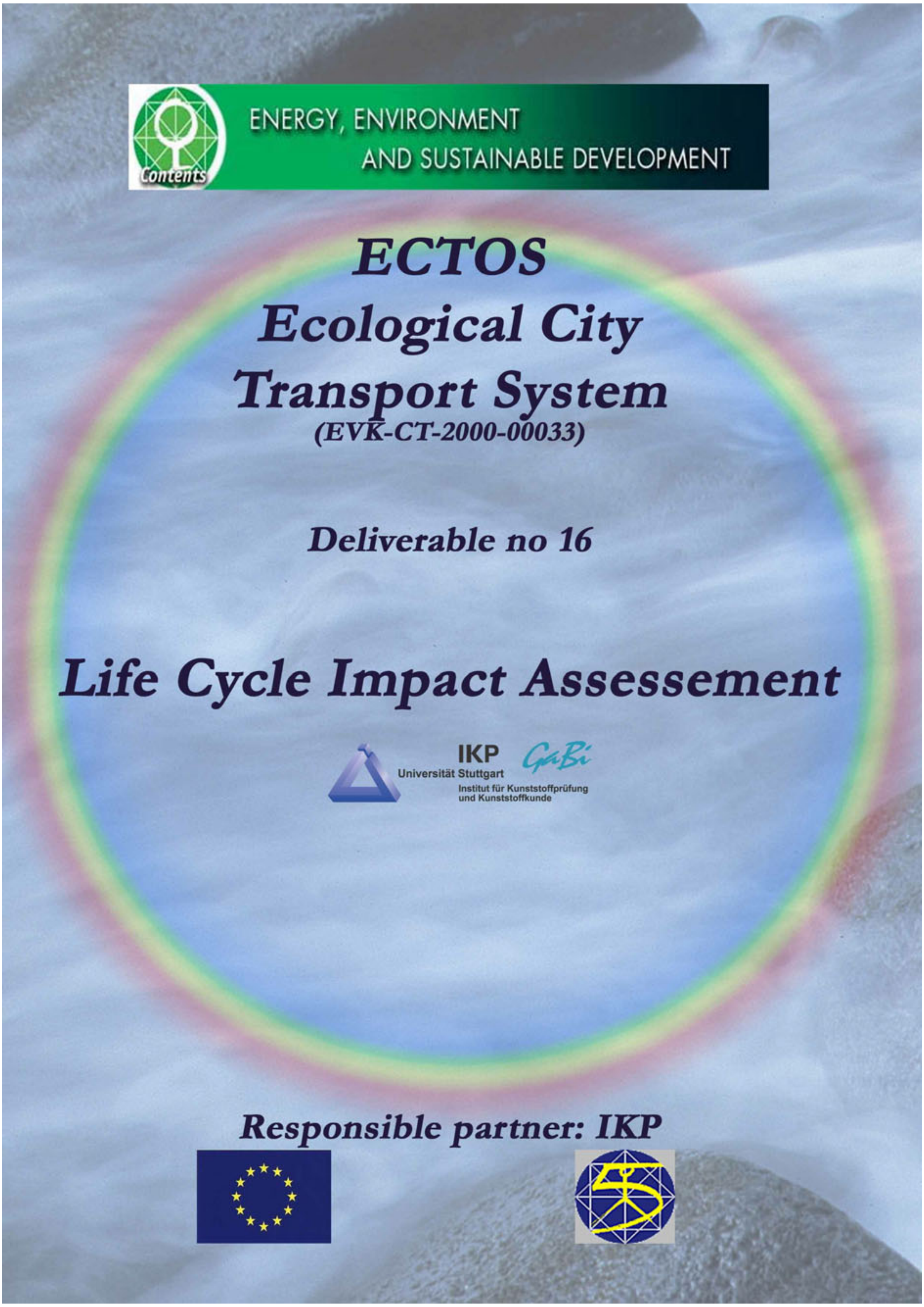

ENERGY, ENVIRONMENT
AND SUSTAINABLE DEVELOPMENT

ECTOS
Ecological City Transport System
(EVK-CT-2000-00033)

Deliverable no 16

Life Cycle Impact Assessement

IKP
Universität Stuttgart
Institut für Kunststoffprüfung
und Kunststoffkunde
GaBi

Responsible partner: IKP

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LIST OF ABBREVIATIONS

AP	Acidification potential
AU	Australia (Country Code following the ISO 3166)
CA	Canada (Country Code following the ISO 3166
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CUTE	Clean Urban Transport for Europe (EU project No. NNE5-2000-00113)
DE	Germany (Country Code following the ISO 3166)
DK	Denmark (Country Code following the ISO 3166)
DZ	Algeria (Country Code following the ISO 3166)
ECTOS	Ecological City Transport System
EP	Eutrophication potential
ES	Spain (Country Code following the ISO 3166)
FC	Fuel Cell
GaBi 4	Software System for Life Cycle Engineering (LCE)
GLO	Global
GWP	Global warming potential
HC	Hydrocarbons (equal to VOC)
HD-PE	High-Density Polyethylene
HTP	Human toxicity potential
IEA	International Energy Agency
KOH	Potassium hydroxide
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LY	Libya (Country Code following the ISO 3166)
MJ	Megajoule

NL	Netherlands (Country Code following the ISO 3166)
NO	Norway (Country Code following the ISO 3166)
NO_X	Nitrogen Oxide
OECD	Organisation for Economic Co-operation and Development
PE	Primary Energy
PM	Particulate Matter
POCP	Photochemical ozone creation potential
PP	Polypropylene
ppm	parts per million
PUR	Polyurethane
PVC	Polyvinyl Chloride
RER	Region Europe
RU	Russia (Country Code following the ISO 3166)
SMC	Sheet Moulding Compound
SO_2	Sulphur Dioxide
STEP	Sustainable Transport Energy Project
UCTE	Union for the Co-ordination of Transmission of Electricity
UK	United Kingdom (Country Code following the ISO 3166)
VOC	Volatile Organic Compounds

1 General Aspects

This Life Cycle Assessment (LCA) study was established in the framework of the ECTOS project. The overall objective of the ECTOS project (EC 5th framework program, EVK4-CT-2000-00033) is to tackle the problem of local urban pollution, by offering the solution of using hydrogen for powering part of the transport sector that is with hydrogen fuel cell buses. The purpose is to demonstrate and evaluate a hydrogen based infrastructure for public transport vehicles and the operation of pollution free hydrogen buses in a CO_2 free environment in Reykjavik, Iceland.

The practitioner of the LCA study is the IKP, Dep. Life Cycle Engineering of the University of Stuttgart. Thereby are the main tasks of the IKP to perform a complete LCA of the Hydrogen production route and to calculate the environmental impact of the fuel cell based transportation system manufacture, operation and end of life in comparison to other conventional and alternative bus systems to get comprehensive knowledge of the infrastructure and the chance for a holistic discussion support for future implementation in the energy and transport sector.

The study and the report has been conducted in accordance to ISO 14040 to 14043.

Date of this report is the 31 July 2005.

2 Goal and Scope

The standard ISO 14041 [8] deals with the Goal and Scope definition as the first step of an LCA.

2.1 Goal of the study

Goal of the study was to assess the environmental impacts of the bus system in Reykjavik (Iceland) and to give comparisons to conventional bus systems (Diesel / CNG) as well as to other European cities.

A detailed description of the goals is also given in the ECTOS LCA Methodology report [24] as well as in the Description of Work of the project.

2.2 Scope of the study

The scope of the study includes the system description, fundamental procedures and data requirements. A detailed description of the scope is given in the ECTOS LCA Methodology report [24].

2.2.1 Function and functional unit

The functional unit is a “quantified performance of a product system for use as a reference unit in a life cycle assessment study“[7].

In this study the functional unit for the bus transport system is “driven kilometre with 50 % loading”. As a bus is calculated with a lifespan of 720 000 km (60 000 km/a * 12 a) this unit represents 1 / 720000 of the whole bus system.

Used functional units in the subsystems of the whole transport system (e.g. filling station, electrolyser, steam reformer, diesel supply chain) are “1 kg hydrogen”, “1 Nm^3 hydrogen” or “1 kg diesel equivalent”.

1 kg hydrogen = 11,126 Nm^3 hydrogen = 3,4 l diesel equivalent

2.2.2 System boundaries

A system boundary according to the ISO standard is “the interface between a product system and the environment or other product systems” [7].

The structure of the system boundaries within the LCA study in the ECTOS project is displayed in Figure 2-1. All life cycle phases from resources over production and use to end of life are considered according to the cut-off-criteria. In Iceland the filling station with on-side electrolyser is realised. For system comparison also hydrogen production via steam reforming is considered.

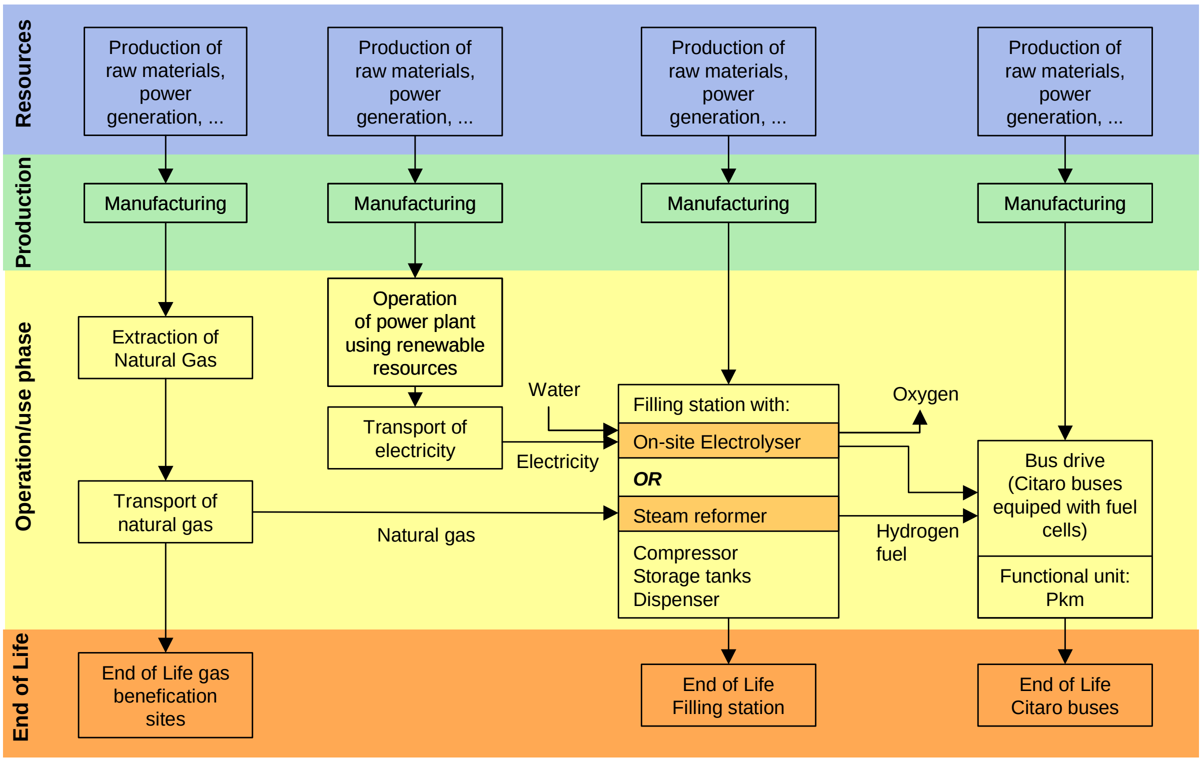


Figure 2-1: System Boundary of hydrogen fuel cell bus system

Figure 2-2 shows the general structure of the life cycle of the hydrogen supply infrastructure, the life cycle of the bus system is shown in Figure 2-3.

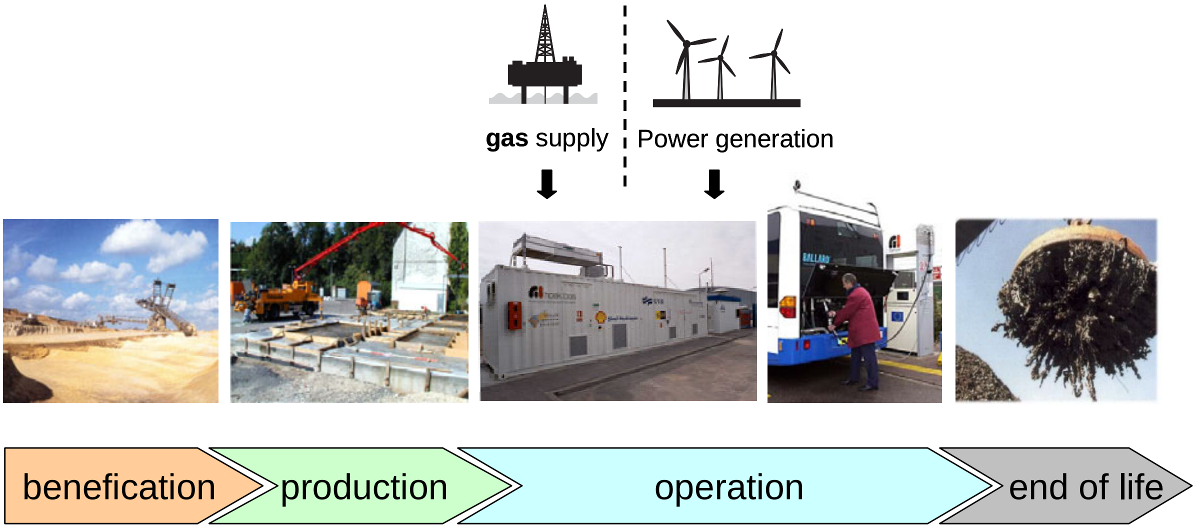


Figure 2-2: Life cycle of hydrogen supply infrastructure

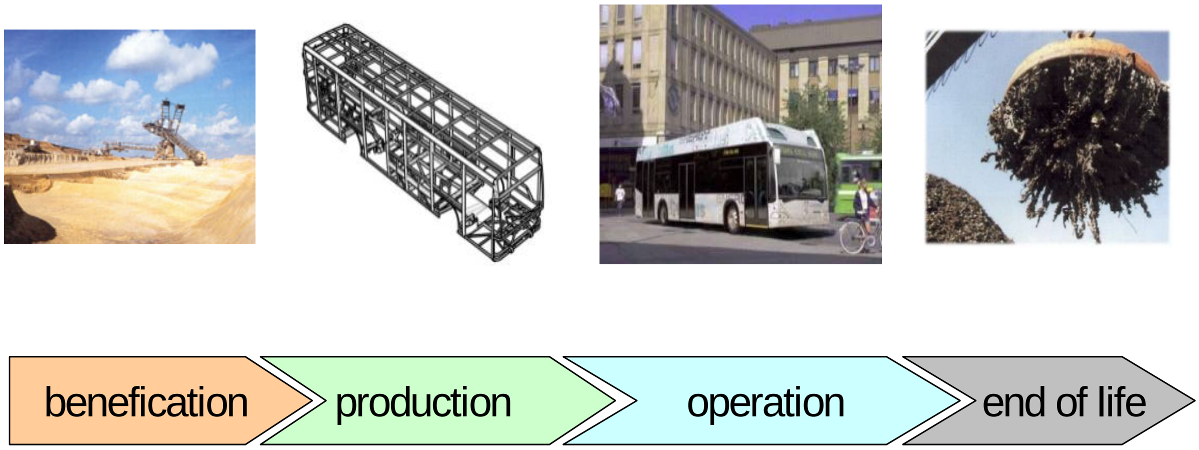


Figure 2-3: **Life cycle of bus system**

Possible supply routes for hydrogen as realised in the demonstration projects ECTOS (Reykjavik), CUTE (Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm, Stuttgart) and STEP (Perth) are shown in Figure 2-4.

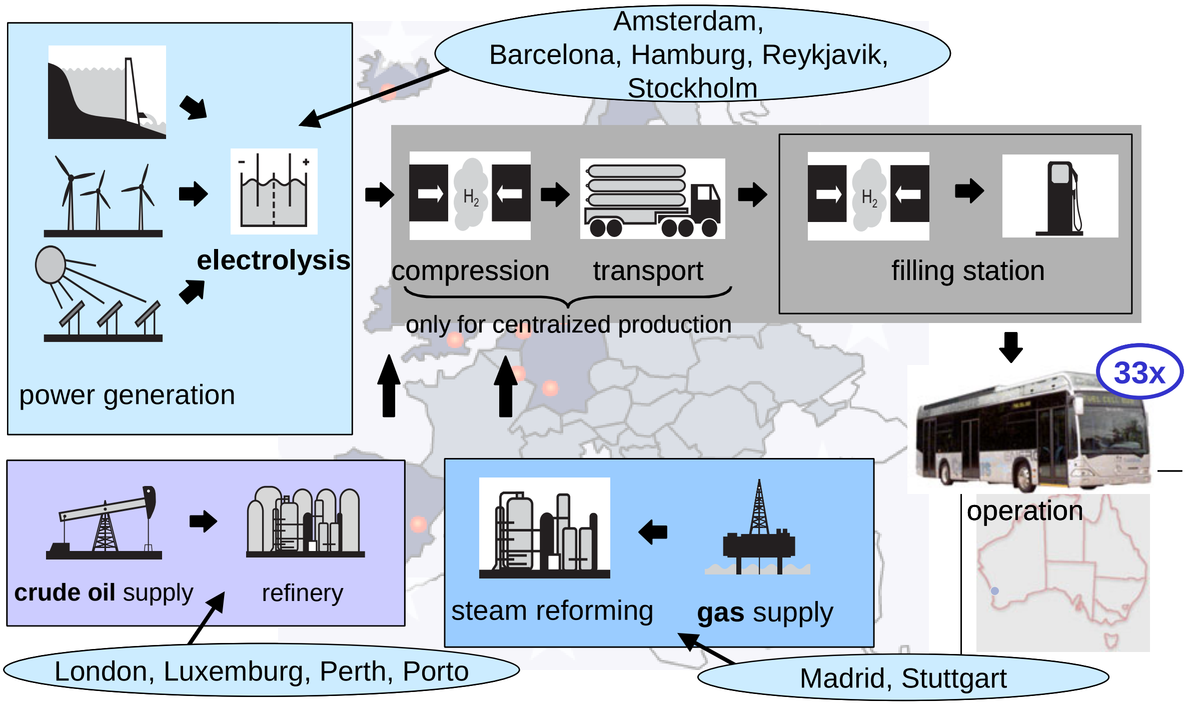


Figure 2-4: **Hydrogen supply routes in ECTOS, CUTE and STEP**

A detailed system description including system boundaries for the different parts like fuel supply and bus as well as cut off criteria is also given in the ECTOS LCA Methodology report [24].

2.2.3 Further methodological issues

A detailed system description including system boundaries for the different parts like fuel supply and bus as well as cut off criteria is also given in the ECTOS LCA Methodology report [24].

DATA QUALITY REQUIREMENTS

The data quality considers precision (measured, calculates or estimated), completeness (e.g. are there unreported emissions?), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, time period, technology). To cover these requirements, first-hand industry data in combination with consistent background LCA information from GaBi 4 database is used

COMPARISONS BETWEEN SYSTEMS

In this study comparisons between different bus systems as well as different fuel supply routes are made. To ensure comparability the system boundary conditions are chosen under equal aspects and represent consistent systems, the systems refer to same functional unit and same cut-off criteria are used.

CRITICAL REVIEW CONSIDERATIONS

An external critical review was not performed within this study.

3 Life Cycle Inventory Analysis (LCI)

3.1 General description of the life cycle inventory

The standard ISO 14041 [8] not only describes the first step Goal and Scope definition, but also the inventory analysis as basis for the LCA.

The main part of an inventory analysis is the data collection. The material and energy flows over the whole life cycle of a product or system are identified. Examples for possible input and output flows are given in Figure 3-1. The flows such as resources, materials, energy carriers, emissions, and wastes can be classified in two groups: elementary and non-elementary ones.

The elementary input flows are input flows which are directly taken from the crust of the earth (e.g. resources, land use). The other inputs must be connected with their respective pre-stages (e.g. manufacturing of fabricated products, electricity generation) and by that the environmental burdens of those processes are taken into consideration as well. The same grouping applies to the output flows. The group of elementary outputs represents flows directly entering the environment (e.g. emissions to air). The outputs flows that receive further processing (non-elementary) need to be connected to their specific downstream process stages (e.g. wastes).

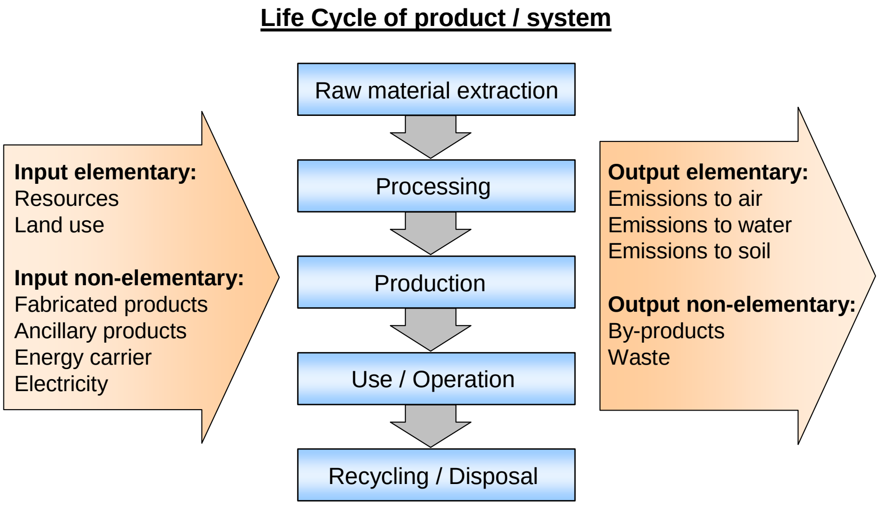


Figure 3-1: Life cycle of a product or system with exemplary input and output flows

It is important to cover all flows throughout the whole life cycle. This avoids a shifting of environmental burdens from one life cycle phase or module to another.

MULTI-FUNCTIONALITY AND ALLOCATION

Processes that provide more than one valuable substance are called multifunctional processes (e.g. combined heat and power generation). The total environmental burdens related to a multi-function process have to be allocated to each valuable substance if the allocation can't be avoided by dividing the multi output process into single output processes or by extending the product system. The quantification of the so-called allocation factors is based on many different methodological criteria. These criteria to quantify the allocation factors can be physical or economic properties of the valuable substances such as calorific value, volume, exergy or market price. Therefore the ISO standard states that allocation is to avoid. However, due to the existence of several multi-output processes within the system allocation is used e.g. for the geothermal power plant, the crude oil refinery. More details are given in the referring subchapters of the following chapter 3.2.

3.2 Data collection and calculation procedures

In this chapter the data gathering and procedures to calculate life cycle inventory are described.

3.2.1 Hydrogen station

DESCRIPTION OF UNIT PROCESSES

This chapter describes the construction, operation and End of Life of a hydrogen station with on-site water electrolyser. The described hydrogen station is situated in Reykjavik. It is equipped with a high pressure water electrolyser module for hydrogen production, a diaphragm compressor module, a high pressure storage module (seven carbon steel torpedo vessels, each with a capacity of 1,365 m^3) and the hydrogen station site with foundation and concrete / steel / glass walls is also included [34], [37]. The H_2 dispenser is integrated in this wall. Auxiliary equipment such as nitrogen bottles, a buffer tank and a closet with shower and a basin to clean the eyes in cases of emergency are part of the hydrogen station site as well. The foundation is made from gravel and concrete.

System boundaries of the hydrogen station

Functional unit is 1 kg = 11,126 Nm^3 of gaseous hydrogen (at 440 bar). Data set considers transport of construction materials, construction of filling station modules itself, hydrogen production via water electrolysis, electricity production from Icelandic sources, operation and maintenance of modules and End of Life phase of hydrogen station equipment.

The station is designed to refuel three fuel cell driven buses and the electrolyser's production capacity is 60 Nm³ GH_2/h at approximately 15 bar. The storage pressure after compression is 440 bar. The performance data can be seen in the tables below.

Estimation regarding H_2 at the hydrogen station (design values)		
"H_2 customers"	3 FC buses	
Estimated re-fills per day	3	
Estimated H_2 demand per bus (38 kg)	423	Nm^3
Necessary H_2 production per day	1.268	Nm^3
Necessary H_2 production per year	462.820	Nm^3

The power demand and the life spans of the different hydrogen station modules is listed in the tables below. A sum of approximately 5,5 kWh / Nm³ (= 61,1 kWh / kg) H_2 is required what is based on design values and the life span of the hydrogen station is set to 30 years. First measurements on electricity demand showed a slight increase but this is yet not confirmed.

Power demand for operation of hydrogen station modules (design values)		
Electrolyser module	5,1	kWh/Nm^3 H_2
Compressor module	0,4	kWh/Nm^3 H_2
Dispenser	0,0004	kWh/Nm^3 H_2
Total	*~ 5,5*	kWh/Nm^3 H_2
Life span of hydrogen station modules		
Electrolyser module	30	a
Electrodes (cell pack)	10	a
Diaphragm compressor module	30	a
Storage module	15	a
Filling station with dispenser	30	a

The transport of the modules to Iceland is included in the described process, the transport of construction materials to the manufacturer is partly taken into consideration as well as the estimated energy demand for the manufacturing of the modules and the hydrogen station foundation.

After reaching the end of the hydrogen station lifespan, the units are decommissioned and a disassembly takes place to recover the main construction materials. The assumptions regarding the waste treatment are listed in the following table.

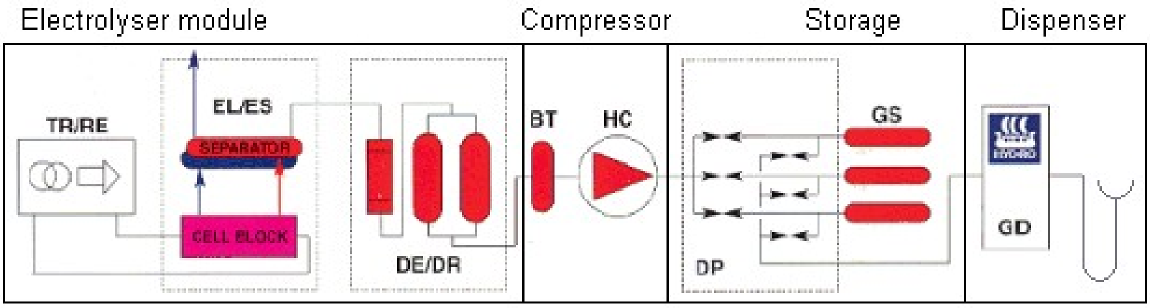
Assumptions concerning waste processing / recycling

Steel scrap	Steel recovery in electric furnace
Copper scrap	Copper processing to get electrolyte copper
Aluminum	Aluminum processing in melting furnace
Used oil	Used oil processing
Demolition wastes: concrete, cement, gravel, glass etc.	Deposition at landfill site
Plastics	Deposition at landfill site
Other wastes (unspecified)	Deposition at landfill site

It is assumed that the materials for recovery are transported back to Europe. The demolition wastes remain in Iceland and get disposed at a dump site. Emissions from the decomposition of materials at the landfill site are not included in this study.

The important material and energy input flows regarding the operation phase are electricity, water and auxiliaries, e.g. hydraulic oil, KOH, exchange diaphragms. The Outputs are Gaseous hydrogen at 440 bar and Gaseous oxygen, which is vented into air.

Flowchart



TR/RE: Transformer/Rectifier
EL/ES: Electrolyser Cell Block/Electrolyser Electrolyte System
DE/DR: Deoxidizer/Dryer
BT: Buffertank
HC: High Pressure Compressor
DP: Distribution Valve Panel
GS: Gas storage
GD: Gas dispenser

Figure 3-2: Norsk Hydro hydrogen station schematic view of the main components including on-site electrolyser [39]

DATA COLLECTION AND DATA SOURCES

The hydrogen station model based on literature data as well as on information of executive persons of Norsk Hydro electrolysers [33], [35], [36], [44], [39], [4] ,[1], [2].

- Personal communication with several staff members of Norsk Hydro electrolysers
- Technical drawings und information
- Knowledge by existing projects
- Own investigations and calculations

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system based on the technical process flow model of the process[1].

VALIDATION OF DATA

The data quality is good, it contains consistent industrial based data for the construction and operation of the main modules and additional literature data (mainly regarding operation phase). The transport distances for the materials are estimated.

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[1] For more information on the GaBi 4 software, see GaBi 4 manual

ALLOCATION PROCEDURES

No specific allocation has been necessary as the only valuable product is hydrogen.

3.2.2 Electrolyser

DESCRIPTION OF UNIT PROCESSES

The main component of the electrolyser unit is the electrolysis module where the water electrolysis processes takes places, see red component within Figure 3-3. Within this module the pre treated water (H_2O) is chemically split into its basic elements hydrogen (H_2) and oxygen (O_2). The reaction takes place at the electrodes, which are placed in an ion-conducting electrolyte. An inorganic membrane is preventing the produced hydrogen and oxygen to reunite again. As shown in Figure 3-3 the hydrogen is further handled by several processes to reach the required purity.

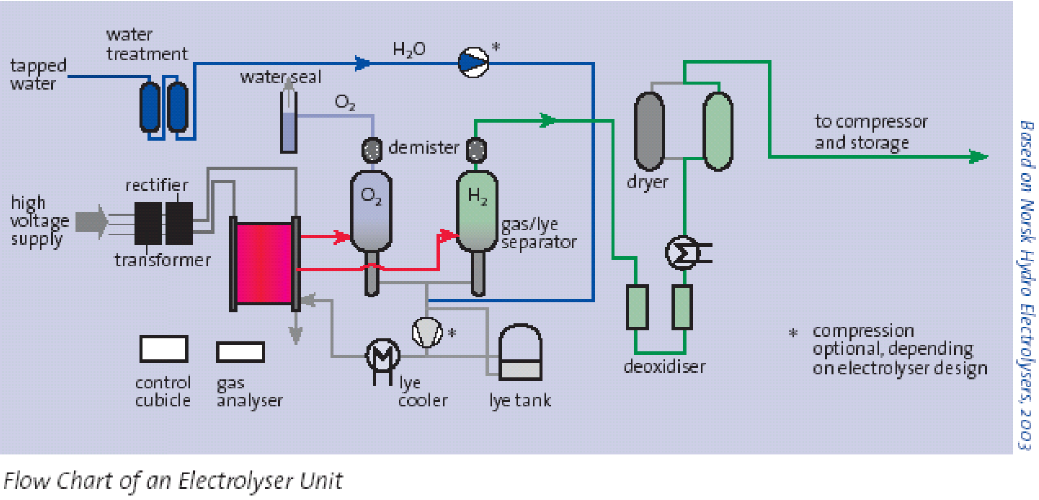

Figure 3-3: Electrolyser unit – flow chart [17]

The major components covered by the LCA of the electrolyser unit are listed in Table 3-1 and the material composition is illustrated in Figure 3-4. The model describes a decentralised electrolyser with a capacity of 60 Nm^3/h.

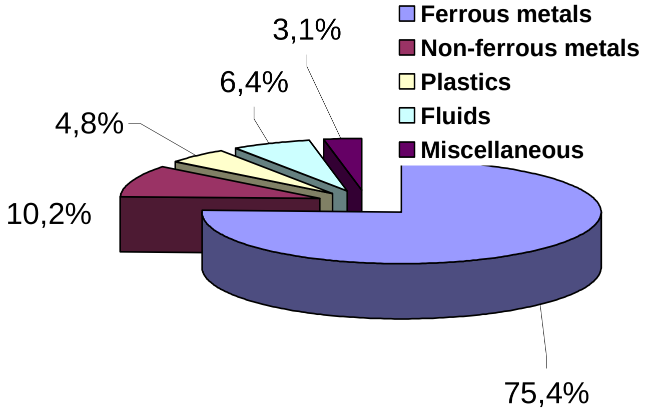

Figure 3-4: Electrolyser unit – material comp.

Main parts of Electrolyser unit
Container
Control Panel
Transformer
Gas/Lye Separator
Electrolyser Module
Cooling Unit
H_2 Drier & Deoxidizer
Feed Water Treatment
Water Purifier
Rectifier
Compressor
Piping & Brackets
Fittings & Instruments
Wiring
Nuts & Bolts

Table 3-1: Electrolyser – main components

Table 3-2 states the energy consumption, the assumed operation time and the maintenance intervals for the main components. These numbers are based on averaged design values given by equipment suppliers. Measurements at the facilities indicate an increase of electricity consumption up to 10 %. The End of Life phase of the electrolyser unit is also covered. The recovery rates are material specific and are assumed to be between 70 % (plastics) and 98 % (steel).

referred to 1 Nm^3 H_2 at 440 bar	Electrolyser	Compressor (membrane)
Time of operation	20 years	30 years
Usage		
power (total)	5,5 kWh/Nm^3	0,35 kWh/Nm^3
Maintenance		
Electrolyser module	7-10 years	
mol sieve	10 years	
catalyst	10 years	
membrane		4000 h
oil		36 kg / year

Table 3-2: Electrolyser – operation

Plastics are handled by energy recovery while metals are recycled.

DATA COLLECTION AND DATA SOURCES

Information on the electrolyser module (parts list) and the operation has been provided by the manufacturers. LCI data sets of materials, energies, production- and recycling processes have been taken from the GaBi 4 database [23].

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system[1] based on the technical process flow model of the process, see Figure 3-3.

VALIDATION OF DATA

To ensure data quality the inventory data has been discussed within a workshop with the equipment suppliers (steam reformer, electrolyser and compressor) and validated with other studies, e.g. [16].

ALLOCATION PROCEDURES

No specific allocation has been necessary as the only valuable product produced by a decentralised electrolyser is hydrogen.

3.2.3 Electricity production in Iceland

DESCRIPTION OF UNIT PROCESSES

The total installed capacity in Iceland at the end of 2001 was 1.458 MW and the total power generation in 2001 was 8.033 GWh. This power generation was provided by 633 power plants. 90 power plants are public power plants with an installed capacity of 1.427 MW and 543 plants are private ones with an installed capacity of just 31 MW. Those private plants are hydro power plants (192) or conventional thermal plants (351) but they just contribute 0,1 % to the total power generation in Iceland [38].

System boundaries of the electricity supply

The conventional thermal power plants (the 351 private plants and 55 public ones) are due the minor relevance in the total power generation neglected for further considerations. The main focus therefore lies on power generation from the public hydro and geothermal power stations as described in the following. By this, Figure 3-5 shows the Icelandic power grid mix:

---

[1] For more information on the GaBi 4 software, see GaBi 4 manual

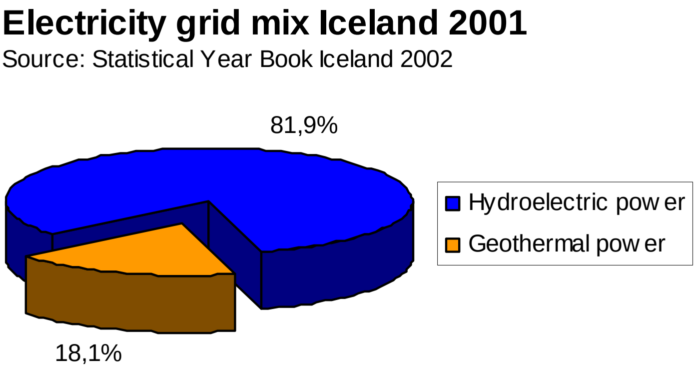

Figure 3-5: Electricity grid mix Iceland 2001, [38], [25]

Data set considers the operation as well as the construction and End of Life of the two dominant power plant types in Iceland: hydroelectric power plants and geothermal power plants. The grid losses and power plant's own electricity demand are also taken into account.

Functional unit is 1 kWh of electricity form the National Icelandic grid.

The following power plant efficiency figures were taken:

	η
Hydroelectric power	86 - 88 %
Geothermal power	17 %

Power transmission and own-use

The highest voltage level is 220 kV for the transmission lines in the South-West of Iceland where most of the Icelandic population lives (e.g. in Reykjavik and Hafnafjördur); most of the biggest hydro power plants are located in the south as well.

The "ring circuit" that provides electricity around the island is a 132 kV transmission line and the distribution of electricity in the local nets is carried out at lower voltage levels (e.g. 66 kV) down to finally 220 V for the urban nets respective the households.

For Iceland, an average loss figure of 4,08 % is given in and the own-use is calculated to be 4,29 %. Those figures are taken for this study.

Hydro Power

Our model describes the construction, operation and end of life of a reservoir hydro power station in Iceland. The emissions and energy demand for the construction are taken into consideration as the emissions during the operation phase are relatively low due to the Icelandic boundary conditions (climate and vegetation).

The power station at Blanda in the northern part of Iceland forms the basis of our model. It is a power plant that uses water from several reservoir lakes that is retained by three dams, the station has 150 MW installed capacity (three 50 MW Francis turbines) and an annual power generation capacity of 720 GWh (gross head is 287 m). It is considered to be a representative Icelandic hydro power plant as it is one of the reservoir plant type as most of the larger plants in Iceland are (only some Icelandic plants are run-off-river plants), in addition it is one of the biggest plants. For further information see Appendix A.

Geothermal Power

The modelled geothermal power plant is of the flash steam type and is an average representative state-of-the-art plant. It is an averaged plant in dependence on Icelandic power plants. It consists of geothermal production wells (with well head and silencer), steam separators and exhaust, mist eliminators, power plant buildings such as turbine hall and control house, a cooling tower and the collection pipes that transport the hot water and steam from the production wells to the equipment and back to wells for re-injection.

The modelled power plant has a 30 MW installed capacity with ~250 kWh annual power generation capacity.

The main parts of a 30 MW state-of-the-art geothermal power plant are:

- Five well heads with silencers for the five production wells to provide controlled hot water pressure for the collection system and noise reduction.
- Two steam separators to separate steam from geothermal brine/hot water
- One steam exhaust for pressure regulation
- Two mist eliminators to remove moisture from the steam
- Turbine hall with steam turbine, 30 MW generator and condenser
- Control building
- Cooling tower
- Collection pipes and other interconnecting pipe-lines

For further information see Appendix A.

DATA COLLECTION AND DATA SOURCES

The electricity grid mix based on literature data as well as on information of operators.

- Statistics of different organizations, e.g. Statistics Iceland
- Professional journals and manuals about hydro- and geothermal power
- Studies and research reports
- Personal information of executive persons
- Knowledge by existing projects
- Own investigations and calculations

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system based on the technical process flow model of the process[1].

VALIDATION OF DATA

The data quality is good. Detailed statistics were available.

ALLOCATION PROCEDURES

- Hydropower: No specific allocation has been necessary as the only valuable product is electricity.
- Geothermal: Combined heat und power production. Allocation by exergy (electric : thermal = 3:1).

3.2.4 Electricity production in Germany

DESCRIPTION OF UNIT PROCESSES

The process describes the electricity generation in utility power plants in Germany according to data from the German Association of power producers (VDEW).

System boundaries of the electricity supply

The given grid mix refers to final energy (see Figure 3-6). All relevant country specific fuel supply processes were included (reference year for fuel supply mixes: 2001, except natural gas: 2002).

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[1] For more information on the GaBi 4 software, see GaBi 4 manual

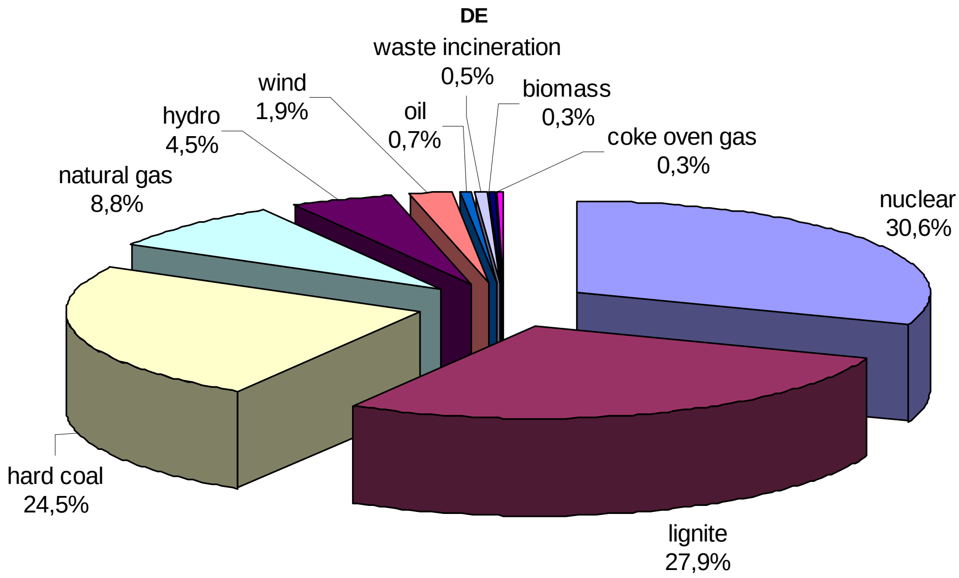

Figure 3-6: Electricity grid mix Germany 2001, [46]

The grid losses and power plant's own electricity demand are also taken into account.

Functional unit is 1 kWh of electricity form the National German grid.

The following power plant efficiency figures were taken:

	η
Nuclear power plant	32,2 %
Hard coal power plant	40,6 %
Lignite power plant	37,5 %
Natural Gas power plant	47,9 %
Hydroelectric power	84 %
Wind power plant	40,0 %
Heavy fuel oil power plant	35,0 %
Waste incineration power plant	20,0 %
Biomass power plant	33,8 %
Coke oven gas power plant	47,9 %

Power transmission and own-use

The following numbers are taken for this study: For Germany, an average loss figure of 4,3 % is given in and the own-use is calculated to be 10,5 %. [46]

DATA COLLECTION AND DATA SOURCES

The electricity grid mix based on literature data as well as on information of operators.

- Statistics of different organizations, e.g. VDEW
- Studies and research reports
- Personal information of executive persons
- Knowledge by existing projects
- Own investigations and calculations

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system based on the technical process flow model of the process[1].

---

[1] For more information on the GaBi 4 software, see GaBi 4 manual

VALIDATION OF DATA

The data quality is good. Detailed statistics were available.

ALLOCATION PROCEDURES

None. (Only power plants producing solely electricity were considered)

3.2.5 Steam reformer

DESCRIPTION OF UNIT PROCESSES

Hydrogen production by steam reforming is based on the conversion of hydrocarbons (e.g. natural gas, naphtha) to hydrogen. The process, as shown in Figure 3-7, mainly consist of pre-treatment of feed (desulphurisation of gas and demineralisation of water), steam reforming, CO-shift and gas purification (pressure swing adsorption – PSA).

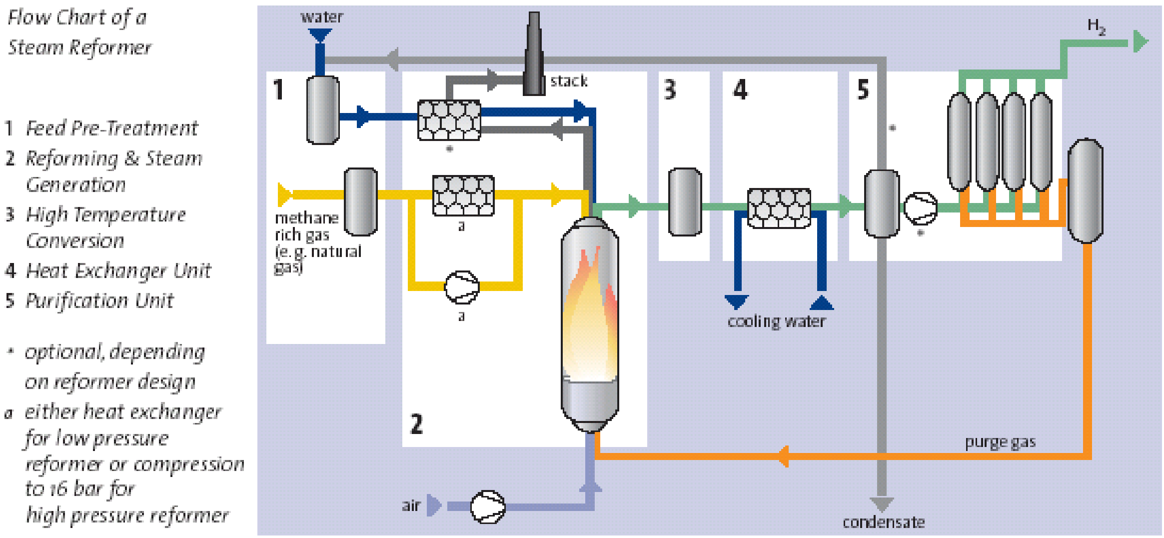

Figure 3-7: Steam reformer – flow chart [17]

The major components covered by the LCA of the Steam reformer module are listed in Table 3-3 and the material composition is illustrated in Figure 3-8 The model describes a decentralised natural gas steam reformer with a capacity of max. 100 Nm^3/h.

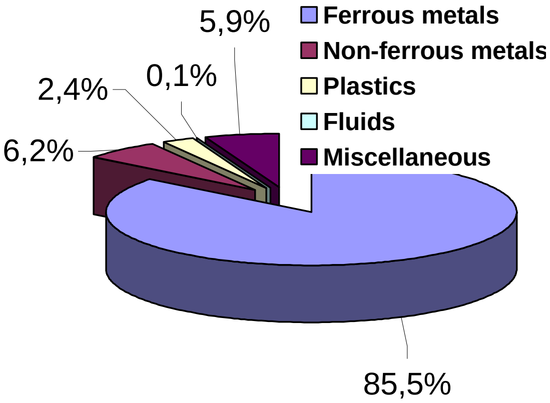

Figure 3-8: Steam reformer – material comp.

Main parts of Steam Reformer unit
Container
Control Panel
Water conditioning system
Sulphur removal reactor
Reformer
CO shift
Product- and tailgas surge drum
PSA vessels
Heat exchanger
Coolers
Compressor
Piping & Brackets
Fittings & Instruments
Wiring
Nuts & Bolts

Table 3-3: Steam reformer – components

Table 3-4 states the energy consumption, the assumed operation time and the maintenance intervals for the main infrastructure components. These numbers are based on averaged design values given by equipment suppliers. The End of Life phase of the steam reformer module is also covered. The recovery rates are material specific and are assumed to be between 70 % (plastics) and 98 % (steel). Plastics are handled by energy recovery while metals are recycled.

referred to 1 Nm^3 H_2 at 440 bar	**Steam reformer**	**Compressor (membrane)**
Time of operation	20 years	30 years
Usage		
natural gas	17,5 MJ/Nm^3	
power	0,44 kWh/Nm^3	0,35 kWh/Nm^3
Maintenance		
reformer module	10 years	
mol sieve	10 years	
catalyst	5-10 years	
activated carbon	2-15 years	
membrane		4000 h
oil		36 kg / year

Table 3-4: Steam reformer – operation

DATA COLLECTION AND DATA SOURCES

Information on the steam reformer module (parts list) and the operation has been provided by the manufacturers. LCI data sets of materials, energies, production- and recycling processes have been taken from the GaBi database [23].

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system [23] based on the technical process flow model of the process, see Figure 3-7.

VALIDATION OF DATA

To ensure data quality the inventory data has been discussed within a workshop with the equipment suppliers (steam reformer, electrolyser and compressor) and validated with other studies, e.g. [16].

ALLOCATION PROCEDURES

No specific allocation has been necessary as the only valuable product produced by a decentralised steam reformer is hydrogen.

3.2.6 Diesel fuel production in Germany[1]

DESCRIPTION OF UNIT PROCESSES

17 petroleum refineries with a capacity of 114,8 10^6 tons per year are operated in Germany. Wherefrom five refineries add to the “Hydroskimming” category (including base oil and bitumen refineries), seven to the “Catcracker”, four to the “Hydrocracker” and one refinery to the “Complex” configuration [32]. All refineries are analysed in our refinery model “GaBi”. The average utilisation of the atm. distillation was 2003: 95,8 % [31].

To get information about the principles of a refinery and their functionality see also the “GaBi 4” database documentation [23].

System boundaries of the diesel fuel supply

The system boundaries of the diesel fuel production are shown in Figure 3-9. The Inputs are crude oil, water, methanol, purchased electricity and purchased natural gas. The Outputs are petroleum products (e.g. diesel fuel), emissions to air and wastewater. Hydrogen has a exceptional position. Depending on the used crude oil, the sulphur limits of the products and the used technology (hydro-desulphurization) Hydrogen is either a product of a refinery or a necessary educt. In Germany it’s assumed that the produced hydrogen (in a refinery) supplied the hydrogen demand (in a refinery).

The fact, that same refineries process intermediate products and use chemicals and additives are due to insignificance unaccounted in our model.

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[1] Iceland imports Diesel fuel mainly from Norway and FSU. A comparison of production of diesel fuel in Germany and Norway is presented in Appendix DI

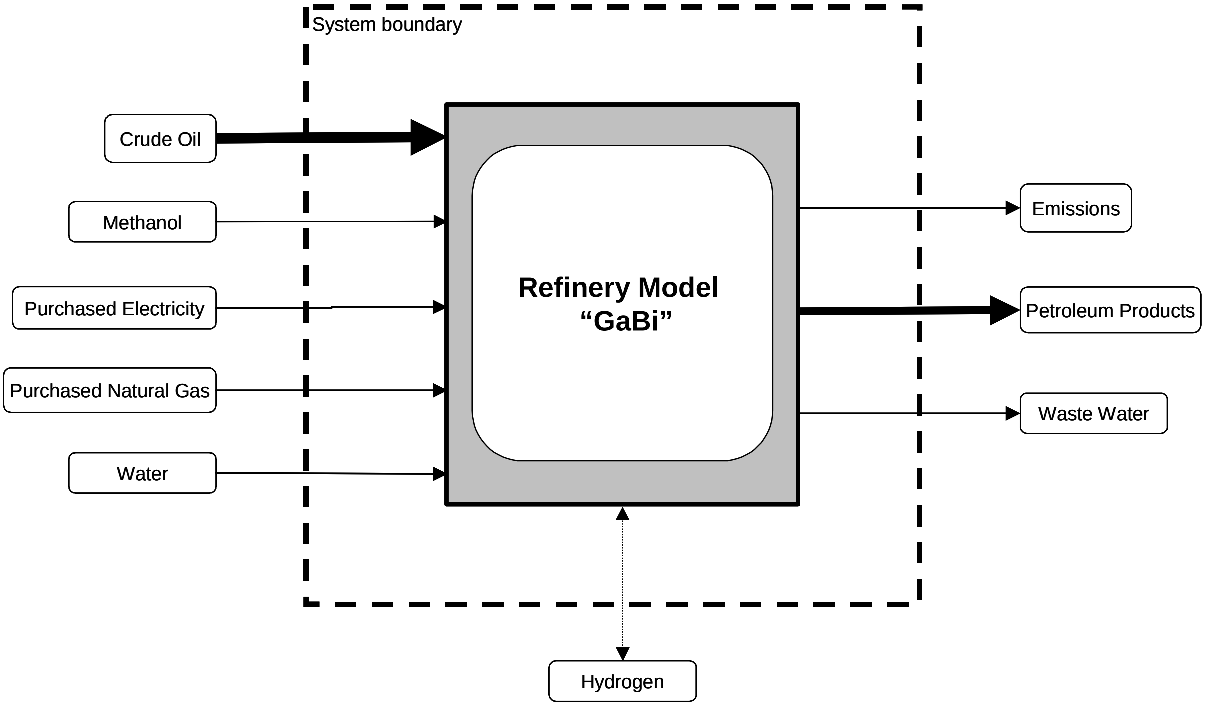

Figure 3-9: System boundaries of the refinery model

Functional unit of the diesel fuel supply

The functional unit of the refinery model is 1 litre of petroleum product, e.g. diesel fuel.

A simplified flow chart of a refinery is shown in Appendix B. The arrangement of these processes varies among single refineries, and few, if any, employ all of these processes.

Relevant properties of the refinery input and output [13], [29], [31].

Crude oil (free refinery Germany):

- Sulphur content: 1,0 wt%
- Density = 0,842 kg/dm^3

Products:

- Sulphur content:

Gasoline:	10 ppm (0,001 wt%)
Diesel fuel:	10 ppm (0,001 wt%)
Light heating oil:	2000 ppm (0,2 wt%)
Kerosene:	2000 ppm (0,2 wt%)

Refinery products

The modelled petroleum product share can be found in Appendix B.

Internal Recycling Flows

The production of the own consumption of fuels is included in the inventories of the products which can be sold. That means, the products, which can be sold, are responsible for the raw material and energy demand as well as the emissions of the fuels which cover the own consumption of the refinery.

DATA COLLECTION AND DATA SOURCES

The refinery model based on literature data as well as on information of refineries.

- Statistics of different organizations, e.g. Mineralölwirtschaftsverband (MWV) [32], Concawe [6], European Pollutant Emission Register (EPER) [3] and International Energy Agency [26].
- Professional journals and manuals about the crude oil treatment [41], [18].
- Studies and research reports [22]
- Personal information of executive persons of refineries
- Knowledge by existing projects
- Own investigations and calculations

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system based on the technical process flow model of the process[1].

VALIDATION OF DATA

The overall data quality is very good, it contains consistent literature data and industrial based data (all relevant flows captured). For the refinery emission inventory different sources (with data of 2000 - 2002) have been used [3].

The consumption of the single stages of the refinery was adjusted, based on average industry values [15].

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[1] For more information on the GaBi 4 software, see GaBi 4 manual

ALLOCATION PROCEDURES

The manufacturing route of every refinery product is modelled and so the effort of the production of these products are calculated specifically.

Two allocation rules are applied.

The raw-material (crude oil) consumption of the respective stages, which is necessary for the production of a product or a intermediate product, is allocated by energy (mass of the product * calorific value of the product).

In these way products with high caloric values, e.g. gasoline or gases are assigned to a higher raw material consumption and so higher environmental impacts compared with low caloric value products (e.g. asphalt, residual oil).

The energy consumption (therm. energy, steam, electricity) of a process, e.g. atmospheric. Distillation, being required by a product or a intermediate product, are charged on the product according to the share of the throughput of the stage (mass allocation).

The products, which are more complex to produce and therefore pass a lot of refinery facilities e.g. gasoline, are assigned with a higher energy consumption (and so higher emissions) compared with e.g. straight run products.

3.2.7 Compressed natural gas (CNG) supply Germany

DESCRIPTION OF UNIT PROCESSES

Natural gas is transferred in pipelines or as liquid natural gas (LNG) in special tankers from the different production countries into the consumer country. The distribution is done under different pressure conditions. There is a long distance pipeline network (pressure > 40 bar), a network for the mid distances (pressure 4-40 bar) and a low pressure network for the service to the end consumer (pressure < 4 bar).

System boundaries of the natural gas supply

The CNG includes the exploration, extraction, processing, the distribution and the compression of the gas. Figure 3-10 gives the composition of the German natural gas supply mix for 2002.

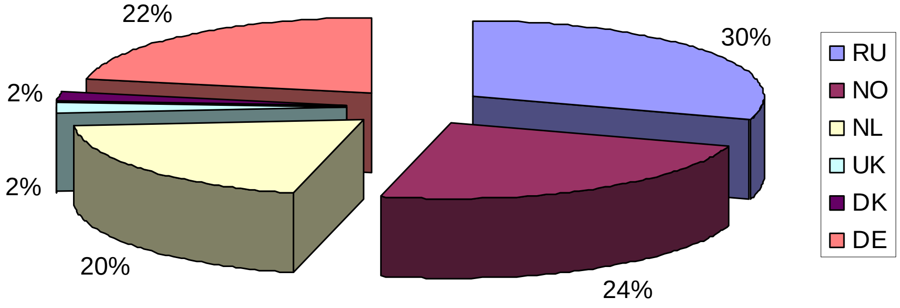

Figure 3-10: Natural gas mix Germany, 2002 [3]

Taken into account are the losses based in the test wells, the leakage, the flaring, the venting, the compressor capability and the pressure gradient. The different county specific power grid mixes are considered. Relevant process data:

Pressure (input):	15 bar
Pressure (output):	250 bar
eta (compressor):	50 %

Functional unit of the CNG fuel supply

The functional unit is 1 kg compressed natural gas free German customer, medium pressure[1] [2]

Relevant properties of the natural gas

Calorific value: 41,501 MJ/kg

Internal Recycling Flows

No internal recycling flows are modelled.

DATA COLLECTION AND DATA SOURCES

Information on the natural gas supply has been taken from the GaBi database [23].

CALCULATION PROCEDURES

The calculation has been performed by the GaBi 4 software system based on the technical process flow model of the process.

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[1] density of natural gas is 1,17 Nm³/kg

[2] free German customer means delivery to a German customer at the indicated pressure level

VALIDATION OF DATA

The overall data quality is very good, it contains mainly consistent literature data (all relevant flows captured).

ALLOCATION PROCEDURES

The share of the associated hauled gas (crude oil gas) is taken into account by its heating value. This is mainly valid for natural gas from the North Sea area.

3.2.8 Bus manufacturing / operation / End of life

The module "bus" is divided in three parts according to its life cycle phases: Manufacturing, Operation and End of life. Following the ISO 14041 structure for each of the three parts a description is given. The process of data collection and the used data sources are briefly described. The used data is validated followed by a description of the applied calculation and allocation procedures

DESCRIPTION OF UNIT PROCESSES

Bus Manufacturing

Starting from the resources, all relevant conditioning-, supply- and process steps are captured in the production phase. Within the production phase the several working steps of the EvoBus factory in Mannheim are modelled as unit processes. They consider the direct inputs and outputs of a process (e.g. input: cold rolled steel, output: part). The upstream processes (e.g. steel production) are linked to the unit processes as separate processes including energy supply. The modelling of the production of vendor parts is generally done by using existing processes, included in the "GaBi 4" database [23]. The parts of special environmental relevance are considered in detail in contact with the specific supplier, for example the CNG storage module of the CNG bus.

Figure 3-11 shows the main process steps of the bus manufacturing phase along with the main in- and outputs.

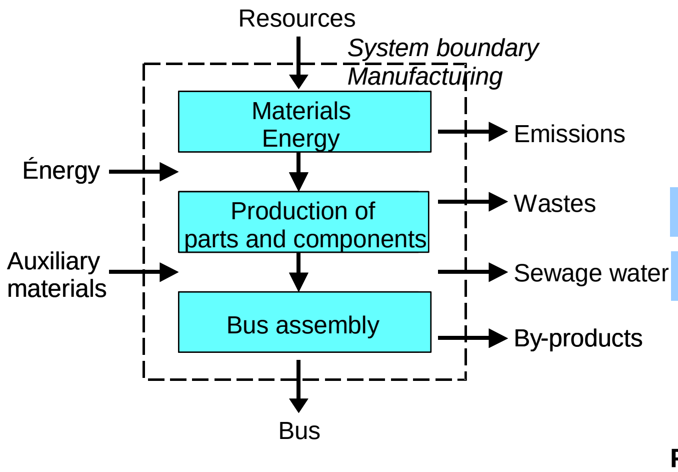

Figure 3-11: Main in- and outputs of manufacturing phase

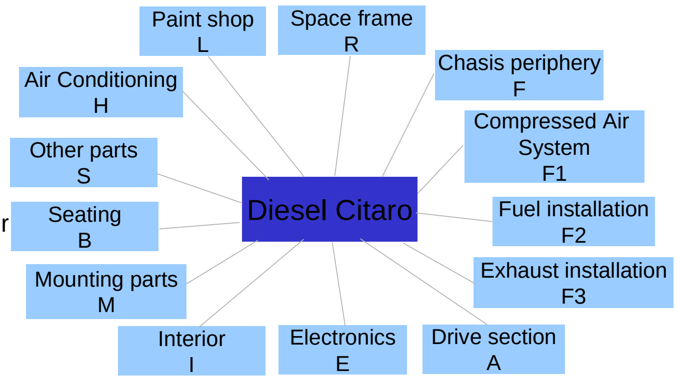

Figure 3-12: Classification of assembly group of a diesel Citaro bus

To be able to compare the diesel version of the CITARO bus with the CNG and FC version the bus was classified into assembly groups which are integrated into a modular model where the diesel bus acts as reference vehicle and the varying assembly groups are exchanged and / or to model the CNG and FC bus respectively. Figure 3-12 displays the assembly groups of the diesel reference vehicle. Table 3-5 describes the main differences between the buses and states the modelled weight for the three bus types. Table 5-2 in the Appendix C gives an overview on the weight differences between the three vehicles

Assemly group	**Code designation**	**Weight [kg]**				
		Diesel	CNG		FC	
			reduction(-)	addition(+)	reduction (-)	addition(+)
Space frame	R	2870		60		120
Chassis periphery	F	582				
Compressed air system	F1	129		1		
Fuel installation	F2	336	314	1030	314	1050
Exhaust installation	F3	68	68	66	45	36
Drive section °	A	3306	970	1176	836	2675
Electronics	E	442			28	95
Interior	I	1423			60	
Mounting parts	M	955		66		177
Seating	B	119			40	
Other parts	S	88			146	50
Air conditioning	H	315		3		
Lacquering	L	100		*		*
Amount		10732	1352	2401	1469	4205
Additional weight			1049		2736	
Total bus		**10732**	**11781**		**13467**	

Table 3-5: Comparison of (modeled) weight of Diesel, CNG and FC bus

* neglectable weight

° including cooling system

The material mix is shown Figure 3-13 and Figure 3-14 for the Diesel and FC bus respectively. The material mix of the FC bus depicts a shift from steel to aluminium in order to save weight. A new material in the mix is carbon fibre used for the hydrogen storage tanks together with graphite used in the FC stacks.

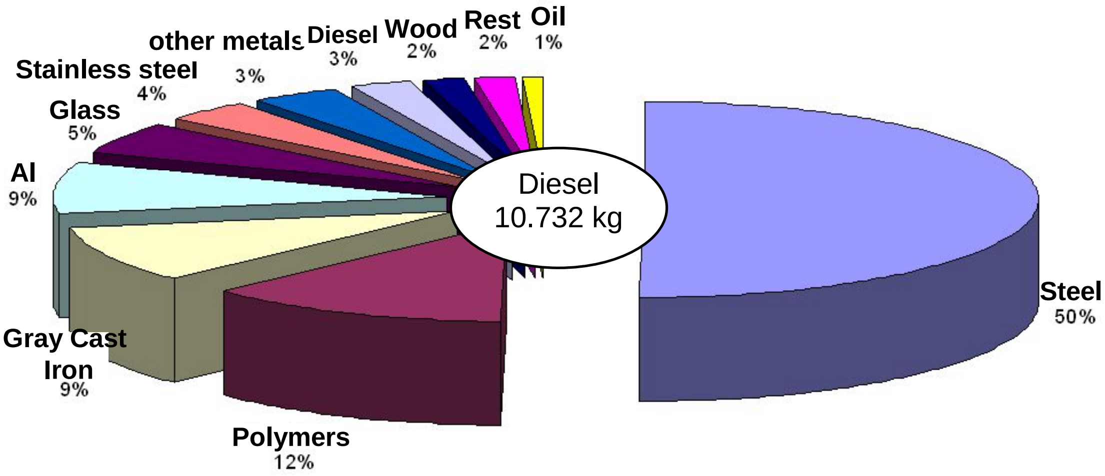

Figure 3-13: Material mix of diesel Citaro bus

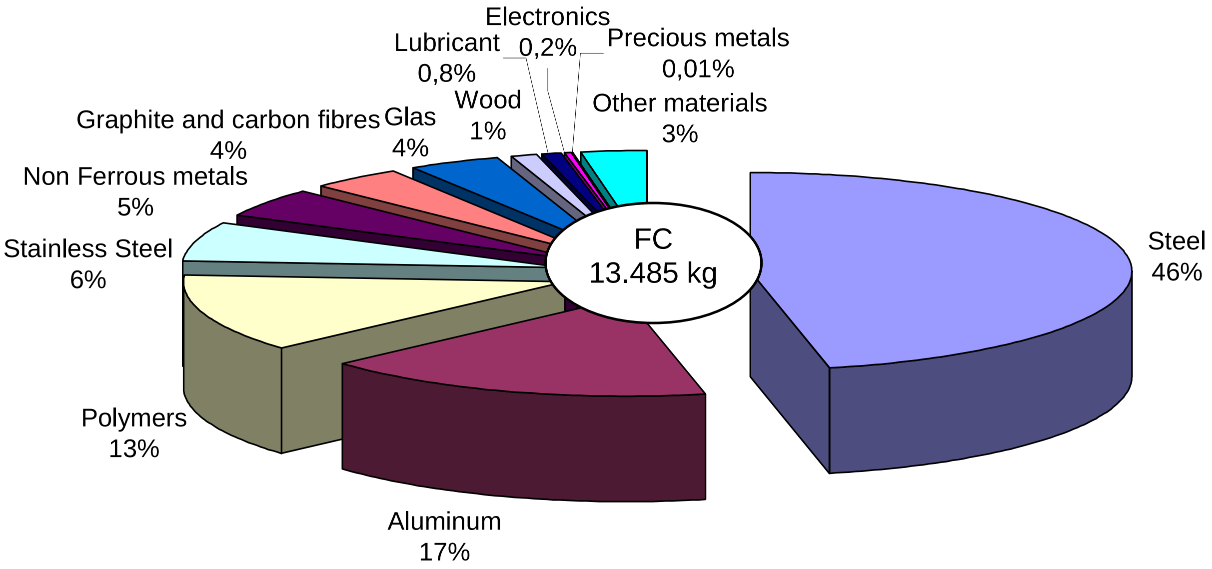

Figure 3-14: Material mix of FC Citaro bus

The material mix of the CNG bus is very similar to the one of the diesel bus. The only variation is related to the fuel storage which leads to an increased steel share (+6 %) and to share of carbon fibre of 4 %, the rest of the materials is scaled down accordingly.

Operation phase

Main input of the operation phase is the fuel and main outputs are the emissions to air caused by the conversion of fuel into propulsion energy (see Figure 3-15). Maintenance parts and auxiliary materials as well as wastes are not considered because they are environmentally irrelevant (relevancy was estimated by doing basic calculations which indicated minimal importance for the life cycle).

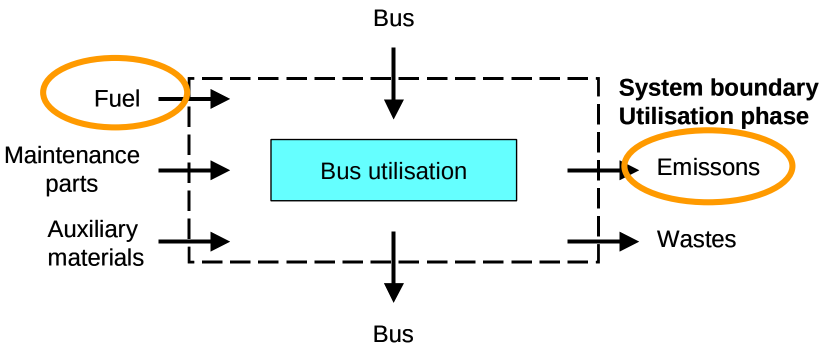

Figure 3-15: Main in- and outputs of operation phase

Fuel consumption and emissions are highly dependant on the routes the buses are operated. More precisely these are dependant a variety of factors such as topographical profile of the route (is it hilly or flat), average speed (as a function of traffic conditions and number of stops) and loading of the bus.

In Table 3-6 three different routes are characterised in more detail. Two are located in Stuttgart and vicinity the other one is a route in Reykjavik.

	Line 42 Stuttgart	Esslingen cycle	Reykjavik Route 3
Lenght [km]	21,5	25,2	27,8
Time required [min]	80	70	90
Number of stops	2 x 27	29	41
Distance between stops [m]	400	900	680
Average speed [km/h]	16	22,3	18,5
Altitude range [m]	240-330	220-290	5-60
Covered altitude distance [m]	534	220	310

Table 3-6: Characteristics of routes the FC bus was operated on

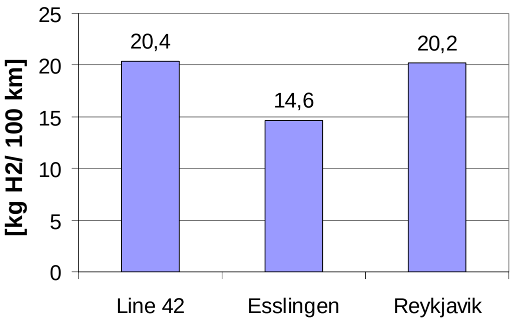

Figure 3-16: Hydrogen consumption of FC Citaro on different routes

Figure 3-16 shows the hydrogen consumption on these routes which was measured in specific test drives with a defined load of 3,5 t (equals around 50 %). Several rounds (3-10 turns) with the same driver were driven on the routes and the consumption was averaged across these rounds.

The consumption values from daily operation analysed over a period of several month on a specific route show for the example of Reykjavik a variation of 20 % and more which can be explained by the influence of different drivers and varying traffic and weather conditions. These kind of variations are not uncommon as literature indicates [42], [11].

Other cities which also operates FC Citaros[1] show average consumption values in the range of 16 to 32 kg hydrogen per 100 km, again highly dependant on the specific local boundary conditions of operation.

In order to compare the FC propulsion system with its conventional competitors diesel and CNG it is essential to have comparable boundary conditions i.e. keep as many parameters comparable. Therefore the following comparison is based on specifically carried out consumption measurements, which were conducted on the two Stuttgart routes. They were conducted as nose-to-tail tests were 2 buses (loaded with 3,5 t) drive right behind each other. The diesel bus served as reference vehicle and was part of each bus pair. Its consumption was used as indicator for the comparability of the measurements.

Line 42 represents a more demanding route with a relatively low average speed, several grades and maximum inclination of 8 % while the Esslingen cycle has a higher share of flat terrain with higher maximum speeds. The speed and altitude profiles are shown in Figure 5-1,and Figure 5-2 in the Appendix C.

The consumption values determined in an overall number of 16 test drives are given in Figure 3-17.

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[1] In the framework of the CUTE project 27 FC Citaros in 9 European cities are tested.

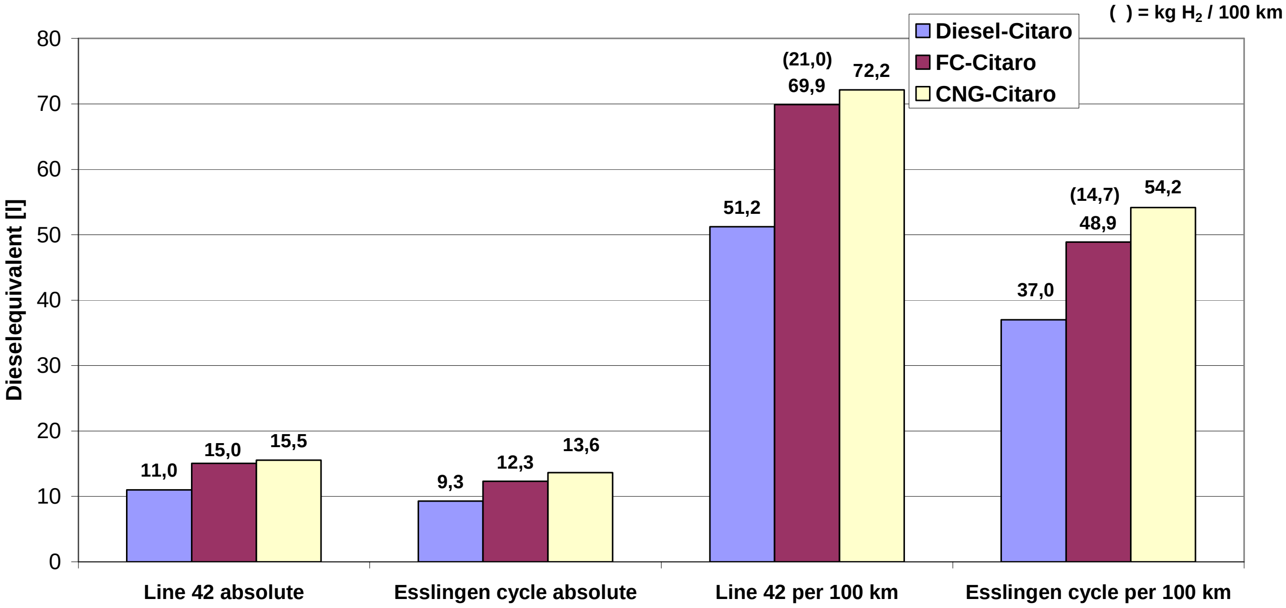

Figure 3-17: Consumption values

Furthermore the emissions for the diesel and CNG bus where measured on a vehicle dynamometer test bench at the University in Graz (Austria) in December 2004. Unfortunately the results were not released for publication by the time this report was written. They will be incorporated in the LCA report for the EC funded sister project CUTE. For this ECTOS report the emissions will be calculated using the engine certification values from EvoBus which are multiplied with the energy output at the rear axle. This energy output is calculated from CAN bus data which is read out via the internal control system of the Citaro bus. For Diesel Euro 5 only the regulatory limits where available. The emission values for diesel and CNG bus, given in [g/km] (see Table 3-7 and Table 3-8), are therefore only meant as indication of the emissions from operation. More accurate values can be expected from the measurements in Graz which will be compared to the calculated emission values. It can be expected that the measured emission values will be higher since the engines are optimised for the certification procedures i.e. the engines show low emissions on the 13 points in the engine map which are relevant for the ESC test procedure. Starting with Euro 4 in 2005/06 a new certification procedure with a transient engine cycle (ETC) comes into affect which has the goal to closer match every day operating conditions.

Line 42	Diesel		CNG	
in g/km	Euro 3 Certif	Euro 5 regulatory limits [ETC]	Euro 4 Certif	EEV Certif
CO	2,63	7,51	0,09	0
NMHC	0,12	1,03	0,12	0,05
CH4			0,21	0,07
NOx	9,88	3,76	7,09	3,56
PM	0,21	0,06	0	0

Table 3-7: Emission values Line 42

Esslingen cycle	Diesel		CNG	
in g/km	Euro 3 Certif	Euro 5 regulatory limits [ETC]	Euro 4 Certif	EEV Certif
CO	2,04	5,82	0,07	0
NMHC	0,09	0,80	0,09	0,04
CH4			0,17	0,06
NOx	7,65	2,91	5,54	2,78
PM	0,17	0,04	0	0

Table 3-8: Emission values Esslingen cycle

End of Life

In the end of life phase the buses are observed from the input of the discarded bus, up to the recycled and worked up materials, energy recovery and waste disposal. Input data is based on the configuration of the manufactured bus. Processes for modelling the end of life phase are taken from the "GaBi 4" database [23].

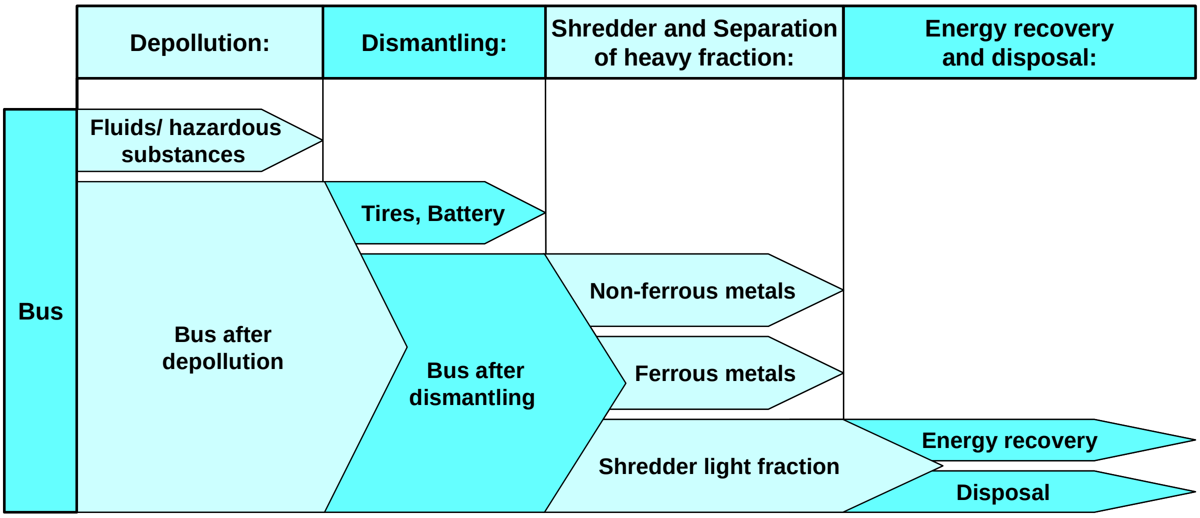

Figure 3-18: Process steps in the end of life phase

Most of the metal and aluminium parts, as well as copper and platinum are recycled. Recycling rates of 98 % for platinum, steel and iron and 92 % for aluminium and copper are considered. A waste incineration plant is fed with the shredder light fraction.

Thus the output of the end of life phase consists of valuable goods for further use and wastes for disposal. For valuable goods and energy it is assumed that they can enter the economic circuit again. They replace a good, material or energy carrier that would have been produced from raw materials. Credits are therefore given for the emissions or primary energy that is related to the production of the respective good which is saved.

DATA COLLECTION AND DATA SOURCES

The production of the Citaro bus was analysed based on the different available bills of materials and machining processes. Data on the production processes for the production of the components was partly collected on site, partly it was estimated using IKP's know how on LCA in the automotive sector in coordination with EvoBus [23]. Figure 3-19 shows the approach taken for data collection at the example of the FC propulsion system supplied by Ballard Power Systems.

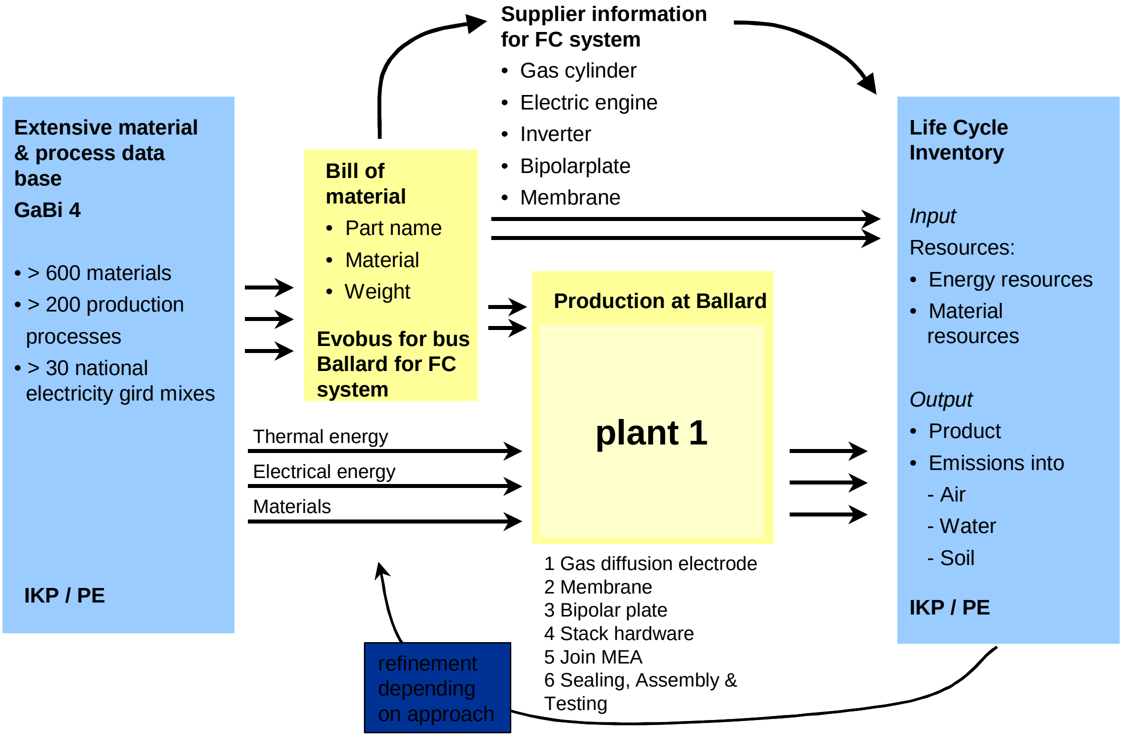

Figure 3-19: Data collection process for bus manufacturing phase

LCI data sets of materials, energies, production- and recycling processes have been taken from the GaBi 4 database.

For the operation phase the data was collected from measurement trials conducted in December 2003, March, May and December 2004. Details are given in chapter “Description of unit processes” in the beginning of chapter 3.2.8.

CALCULATION PROCEDURES

Calculation has been performed using the GaBi 4 software system using the data and information collected in the course of the project.

VALIDATION OF DATA

Data quality and results for all life cycle phases were presented and discussed on several occasions to various experts from the bus manufacturer and from selected key suppliers. For the End of Life of the vehicle standard processes from the automotive industry were used. Their applicability on buses was discussed with the bus manufacturer and it was concluded that they could be used as a first approximation.

Data gaps were closed in coordination with the bus manufacturer and its suppliers either by data enquiry or by expert judgement.

ALLOCATION PROCEDURES

No specific allocation has been necessary.

3.3 LCA modelling of the bus system in GaBi 4

The following chapter gives an overview about the structure of the fuel cell bus system such as is modelled in GaBi 4 and basis of this study. As mentioned in chapter 3.2.8 the life cycle is made up of the following steps (processes): manufacturing, operation and end of life. These unit processes and plans (boxes in Figure 3-20) are linked with arrows, which are called flows. The thickness of the flows represents the mass distribution within a system.

Furthermore the hierarchical plan structure of the model is clarified by means of the following screen shots.

Figure 3-20 displays the total life cycle of a fuel cell bus.

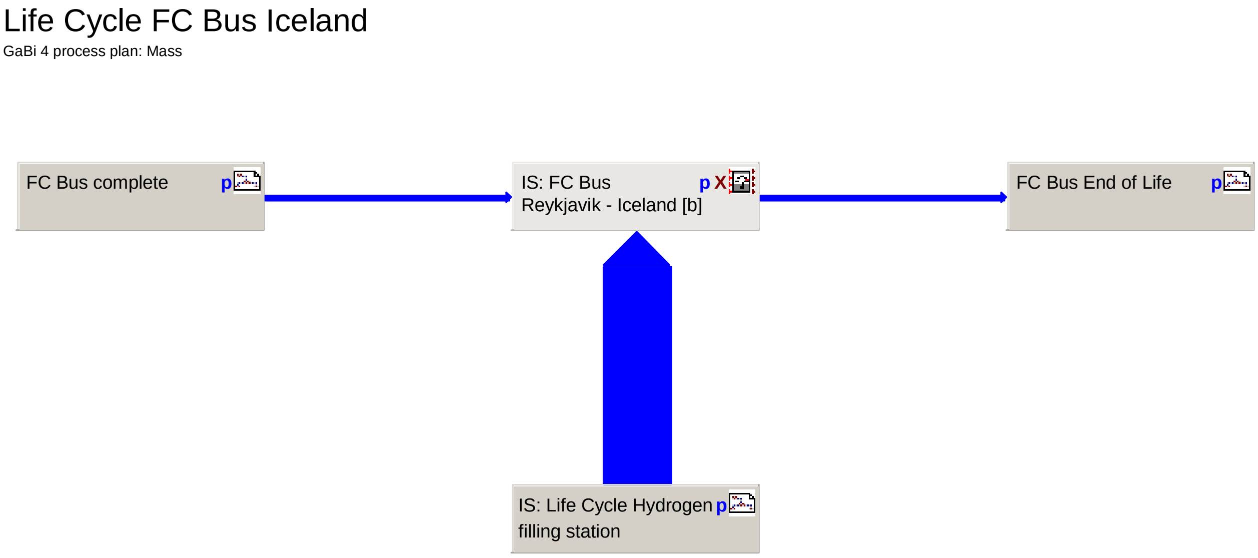

Figure 3-20: GaBi 4 screen shot – Model of the FC bus life cycle

The plans “Life cycle hydrogen station” and “FC Bus complete” will be exemplified below.

LIFE CYCLE HYDROGEN STATION

The Hydrogen station in Reykjavik represents state-of-the-art H_2 production via water electrolysis and the necessary compression and storage as well. The components of the hydrogen station as set up in the GaBi 4 model can be seen in Figure 3-21. The module is divided in four parts: Electrolyser, diaphragm compressor, storage and filling station, including the dispenser.

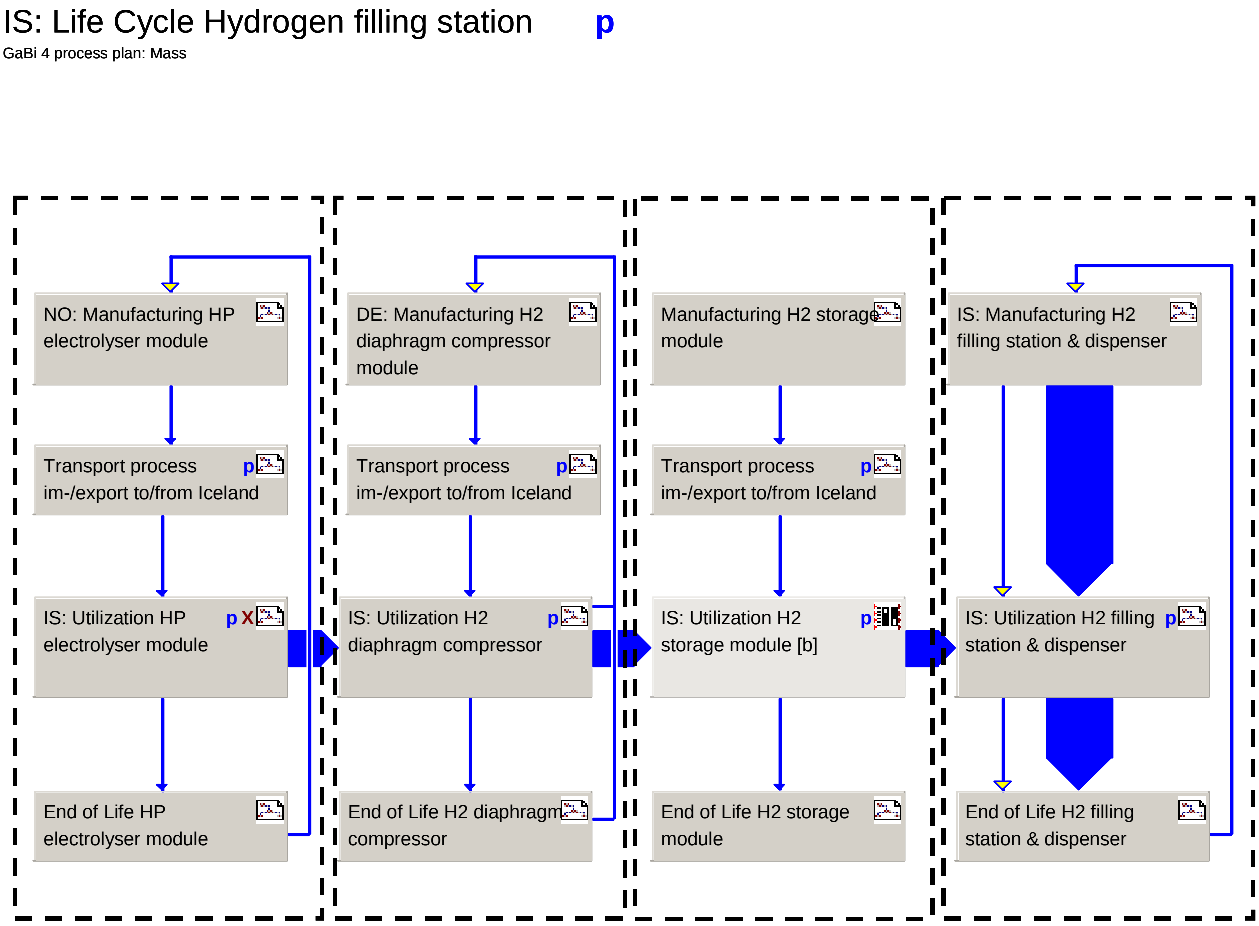

Figure 3-21: GaBi 4 screen shot – Model of the Hydrogen station life cycle

The model is set up on the basis of data and technical drawings from Norsk Hydro Electrolysers, Norway [33], [34], [35], [36], [37], [40], who provide the hydrogen station equipment. Additional information is taken from Andreas Hofer Hochdrucktechnik GmbH; Germany [1], [4], regarding the compressor and from Ferill Ltd., Iceland [45], concerning the foundation and surroundings of the Shell station in Reykjavik.

FC BUS COMPLETE

As noted in chapter 3.2.8, the manufacturing of the bus is classified in assembly groups (due to the comparability, see chapter 3.2.8). For that reason the manufacturing process “FC bus - complete” is divided in two parts: “FC bus basis – complete” and “FC components – complete”. Exemplary, the manufacturing of the additional FC components is shown in Figure 3-22.

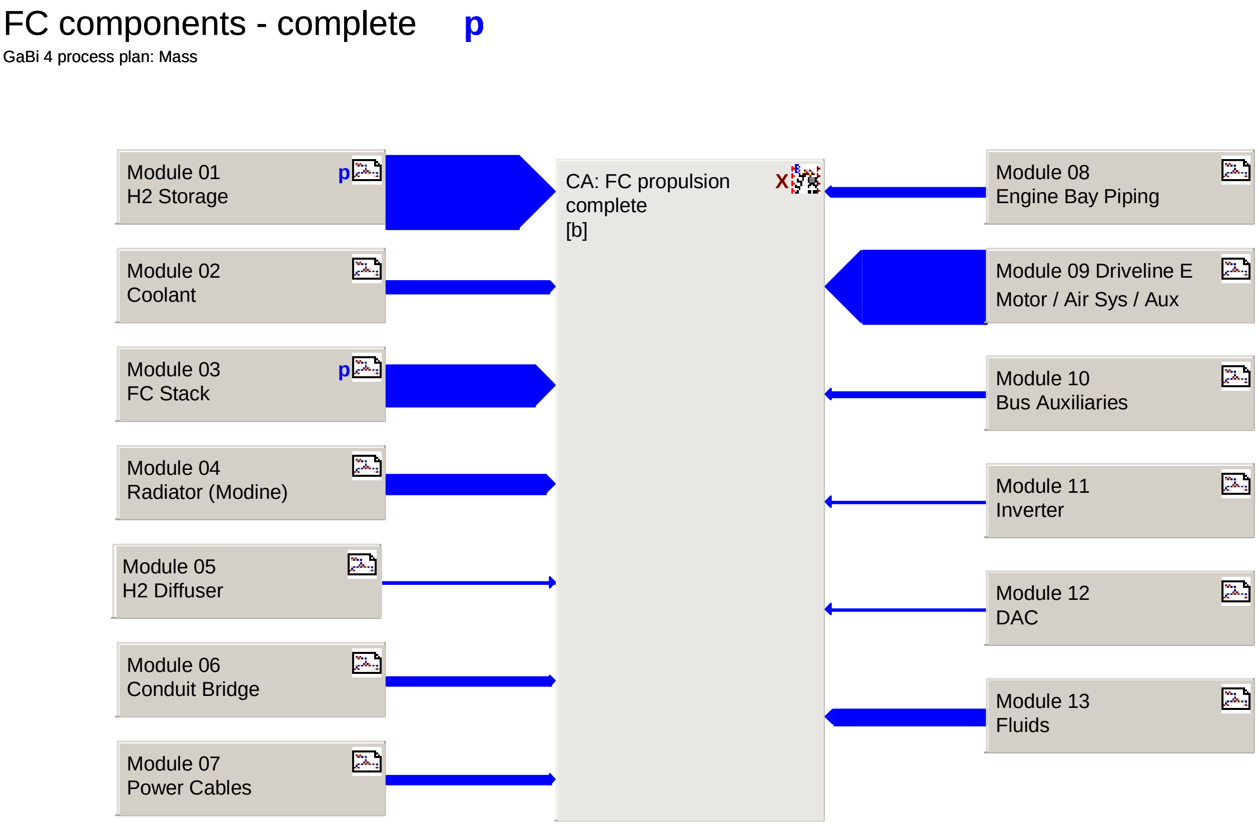

Figure 3-22: GaBi 4 screen shot – Model of the FC components

The considered upstream products are assembled in the FC propulsion process. Relating to the total weight of these process, the H_2 storage and drive section, respectively the drive line are dominantly.

In Figure 3-23 the process “Module 01 H_2 Storage” is shown. The H_2 storage module exists of a H_2 storage cylinder, base frame, piping, valves, end plug vales, pressure regulator and small parts like nuts and screws.

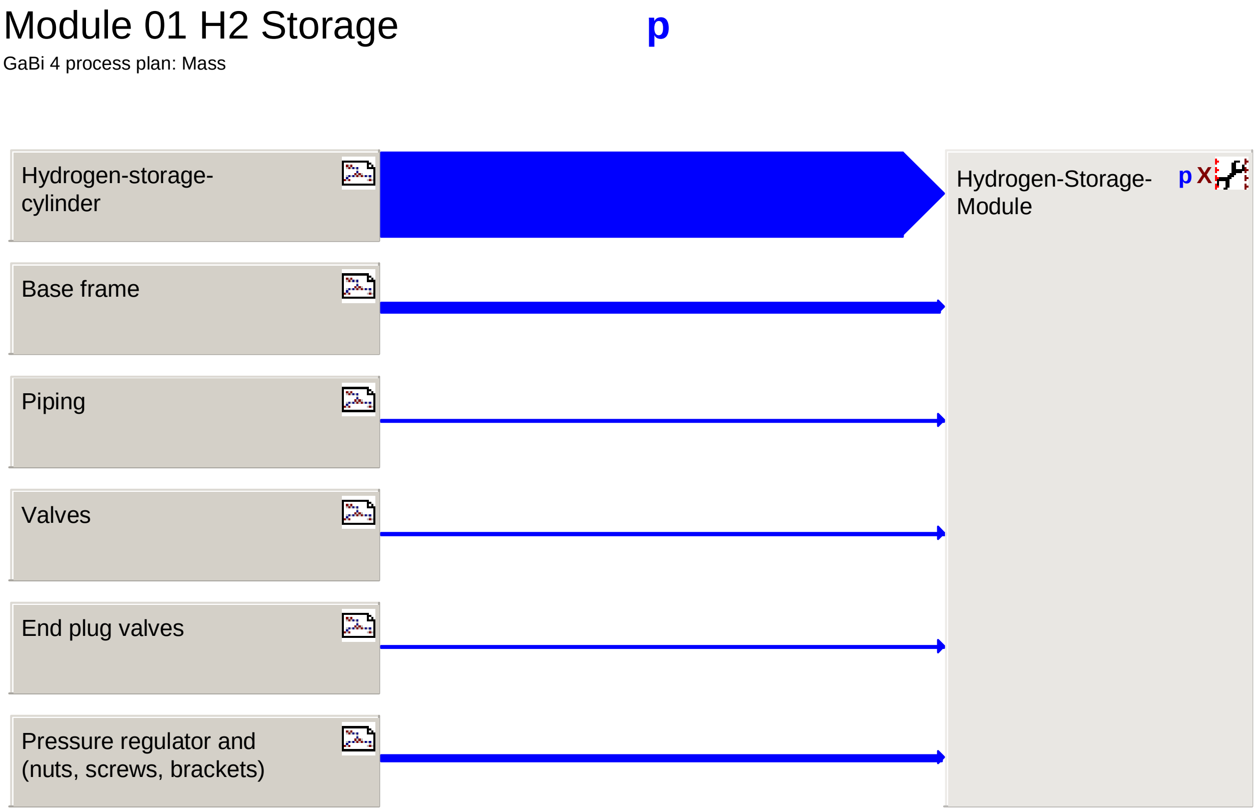

Figure 3-23: GaBi 4 screen shot – Model of the H_2 storage module

Figure 3-24 demonstrates the processing of a “Hydrogen storage cylinder”. Unlike assembly processes, like the storage module, the auxiliaries are due to there relevance modeled. For instance, the lube oil and cutting fluid consumption.

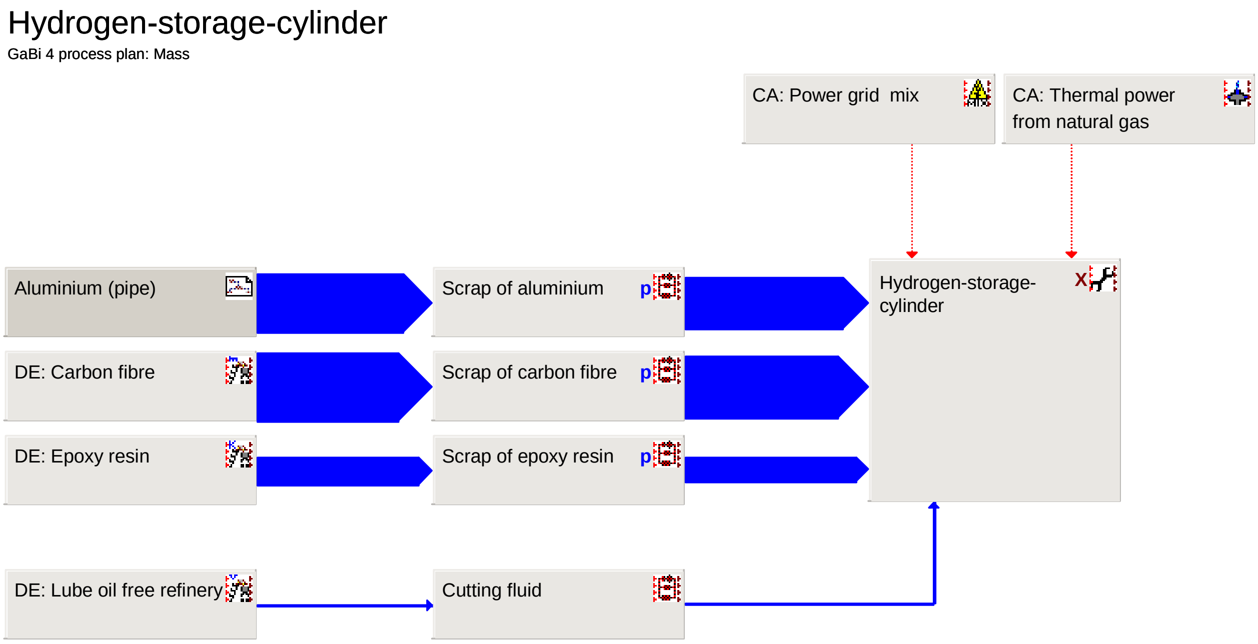

Figure 3-24: GaBi 4 screen shot – Model of the H_2 storage cylinder

The flows electricity respectively thermal energy (connection between the process “Power grid mix” resp. “Thermal power from natural gas” and the “Hydrogen storage cylinder”) are dashed flagged because the reference unit of these flows is energy and not mass (compared with the remaining processes).

Besides the scarps of the aluminum, carbon fiber and epoxy resin processing are considered.

3.4 LCI results

In this chapter life cycle inventory results for hydrogen production in Iceland, for the fuel cell bus system in Reykjavik, for general hydrogen production alternatives (electrolysis and steam reforming with European boundary conditions), for the bus manufacturing and for the bus system comparison are shown.

3.4.1 LCI results of the hydrogen production in Iceland

Hydrogen production in Iceland via electrolyser includes filling station (manufacturing, operation and end of life) and power demand according to Icelandic grid mix (see chapter 3.2.3) as main input.

In general the following diagrams show a column representing the absolute value of primary energy demand or emission related to 1 kg of produced hydrogen in Iceland. The parts of the hydrogen station (filling station foundation and dispenser unit / diaphragm compressor /

storage module / electrolyser module) each include manufacturing, operation and end of life phase. As input to the electrolyser electricity from Icelandic grid is used. These upstream processes are included in the electrolyser module and the share related to hydro power, geothermal power and others (electrolyser module manufacturing, operation and end of life) are shown as percentage in the pie chart.

PRIMARY ENERGY DEMAND (PE)

The primary energy demand for 1 kg of hydrogen is 424,6 MJ as shown in Figure 3-25. Most of this is related to the operation of the hydrogen station because electricity is one of the two main input flows in this life cycle phase (the other is water). The primary energy for the H_2 production is exclusively taken from renewable energy resources, whereas the energy for the manufacturing of the hydrogen station modules is derived from non renewable resources. Renewable resources (hydro power and geothermal power) cover more than 98 % of the primary energy demand and within the power supply 54 % of primary energy is related to hydro power and 46 % to geothermal power.

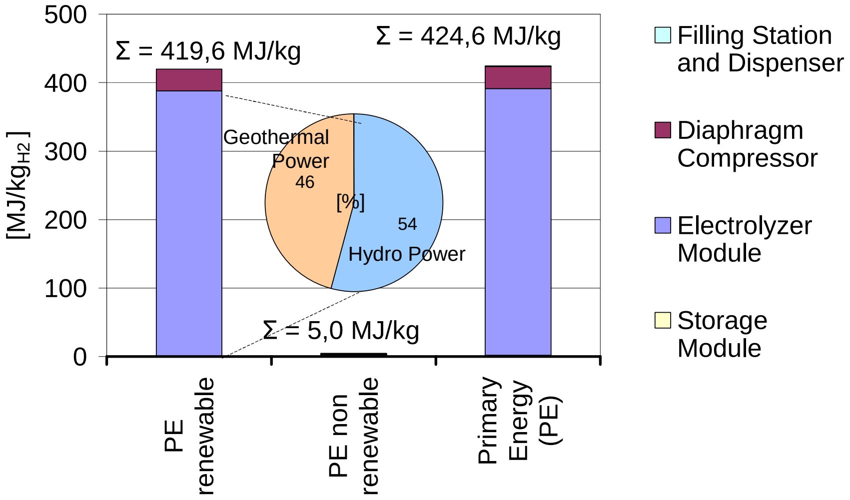

Figure 3-25: Primary Energy per 1 kg of produced hydrogen in Iceland

CARBON DIOXIDE (CO_2)

The main emission into air is carbon dioxide. A total amount of 1074 g/kgH_2 is emitted. Most of the CO_2 emission is caused by the utilisation of the H_2 production facility that needs electricity; it is closely related to the emissions from the power plants. The CO_2 emission from the manufacturing phase of the filling station is dominated by the amount of steel that is used in the storage module and the filling station itself, as well as the volume of concrete that is necessary for the foundation. The emission from the utilisation phase represents the share of electricity needed for the operation of electrolyser and compressor module as the whole emission is related to the power generation.

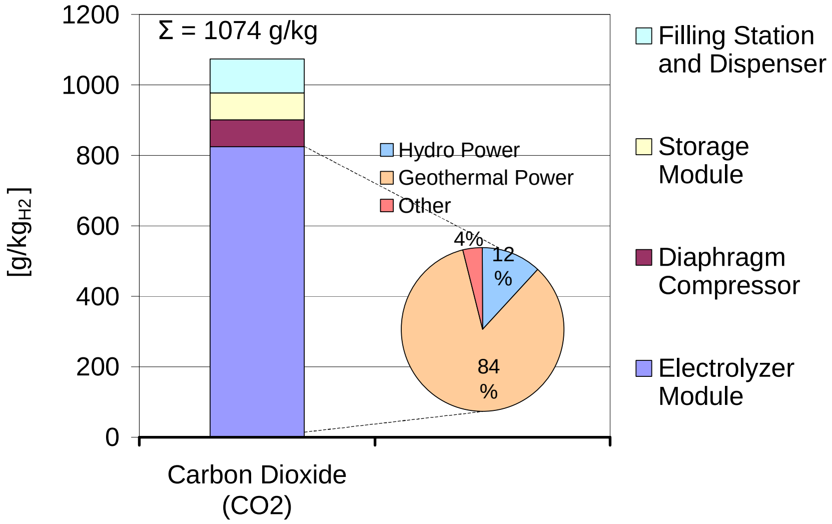

Figure 3-26: CO_2 per kg of on-site H_2 production at the hydrogen station

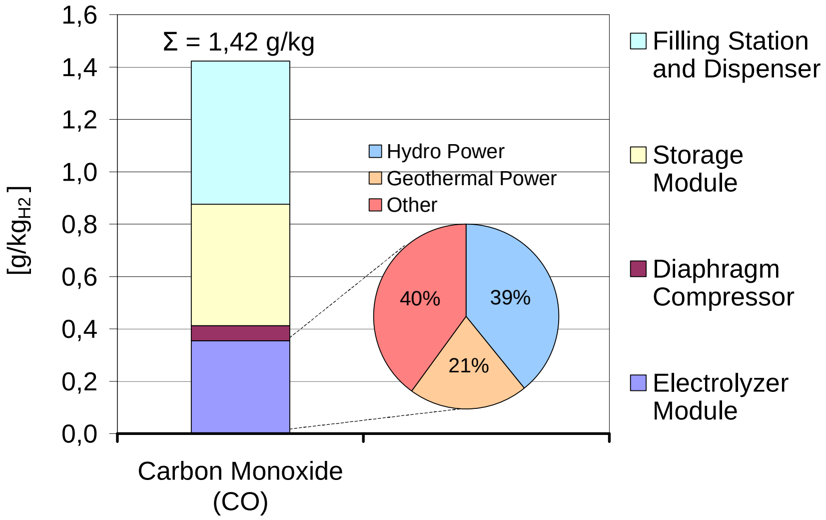

Figure 3-27: CO per kg of on-site H_2 production at the hydrogen station

CARBON MONOXIDE (CO)

CO emissions are relevant for the transport sector and considerations regarding vehicle emissions caused by fossil fuel combustion. The total amount of CO related to 1 kg H_2 is 1,42 g. The emission is mainly caused by the manufacturing processes, just 18 % are derived from the hydrogen stations utilisation phase.

NITROUS OXIDE (N_2O)

Emissions of nitrous oxide derive of more than 80 % from manufacturing of infrastructure components (hydrogen station, power plants) and there from steel production as well as concrete supply.

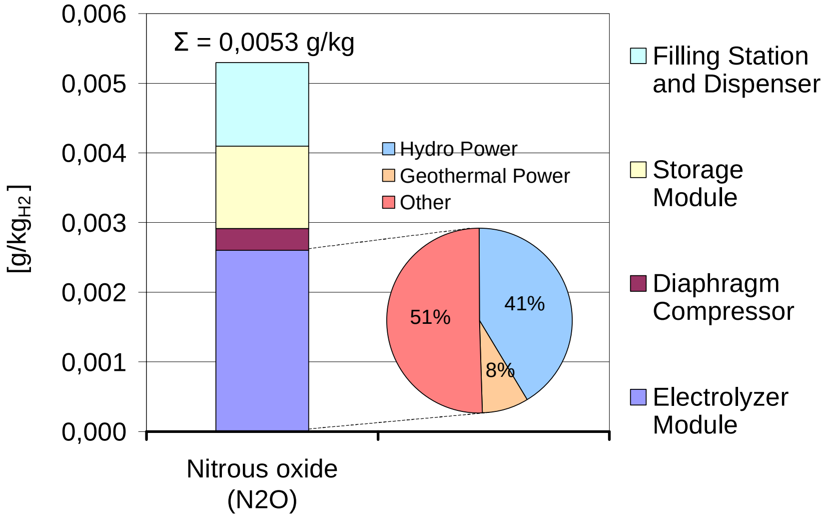

Figure 3-28: N_2O per kg of on-site H_2 production at the hydrogen station

SULPHUR DIOXIDE (SO_2)

A special situation is given for SO_2 emissions as almost 50 % are related to the production of special steel for electrodes. The rest is also mainly related to material production, especially steel.

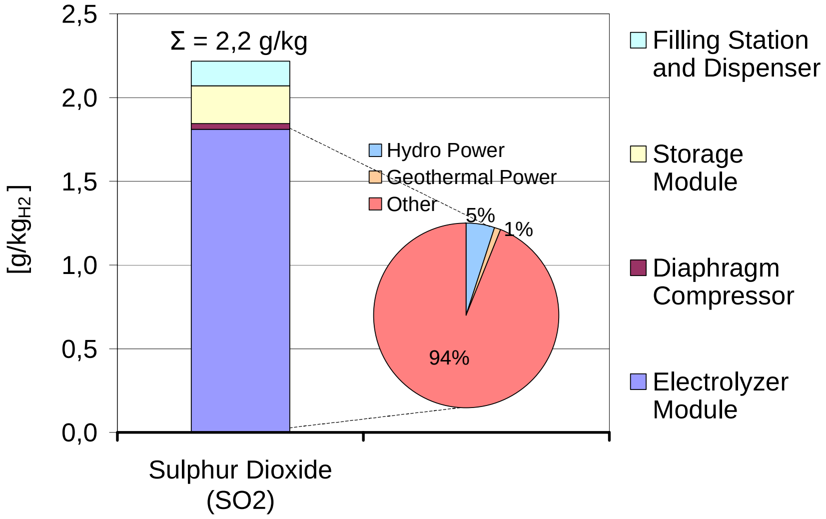

Figure 3-29: SO_2 per kg of on-site H_2 production at the hydrogen station

HYDROGEN SULPHIDE (H_2S)

The influence of the Iceland power generation on the emissions per kg of H_2 gets even more obvious when looking at H_2S. Nearly all of the emitted H_2S during the life cycle comes from the power demand during the utilisation of the hydrogen station and the related emissions from the geothermal power station Figure 3-30. Although the H_2S emission from the manufacturing phase is quite low compared to the utilisation phase.

A more detailed discussion of H_2S emissions from geothermal power generation and the related environmental effects is actually in progress in Iceland and further studies will be performed to cover this issue.

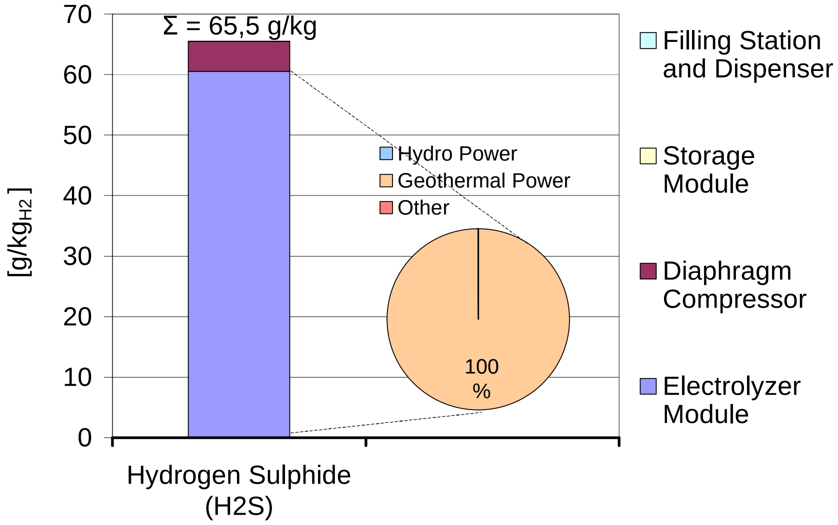

Figure 3-30: H_2S per kg of on-site H_2 production at the hydrogen station

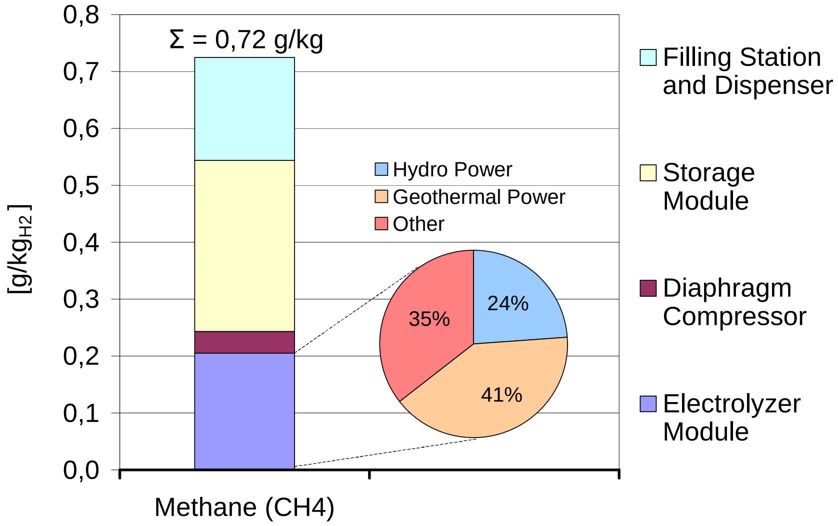

Figure 3-31: CH_4 per kg of on-site H_2 production at the hydrogen station

METHANE (CH_4)

The influence of the operation phase regarding this emission is not as dominant as in the case of CO_2 or H_2S, the prevailing life cycle phase is the manufacturing. The steel production and processing as well as the amount of concrete that is used for the filling station foundation play an important role. So filling station and storage module have main share of the overall methane emissions. The methane emissions from the power generation are therefore just dominant regarding the utilisation phase.

NITROGEN OXIDES (NO_x)

The emission of nitrogen oxides is one of the emissions with a dominant manufacturing phase. NO_x is a typical emission related to the combustion of fossil fuels, e.g. in diesel engines. The manufacturing emission has its origin mainly in the steel production (e.g. for the storage module). The filling station requires reinforced concrete for the foundation what causes NO_x emissions from the combustion of diesel for transport processes of concrete and gravel.

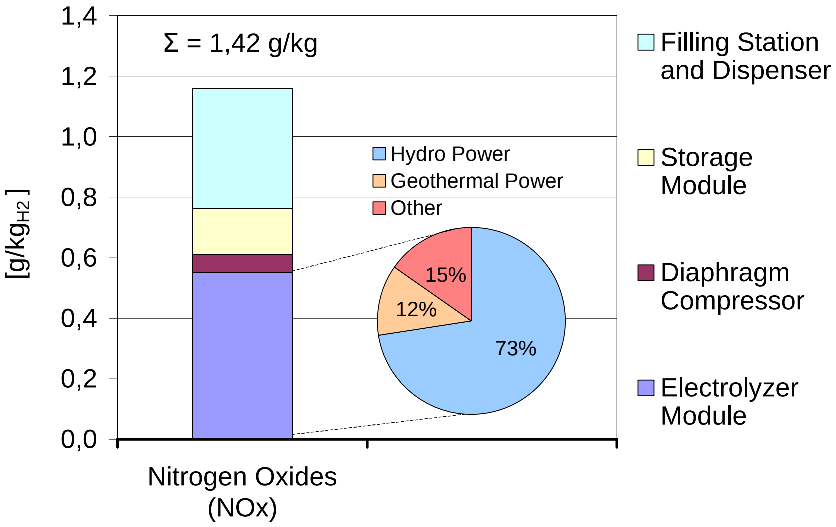

Figure 3-32: NO_x per kg of on-site H_2 production at the hydrogen station

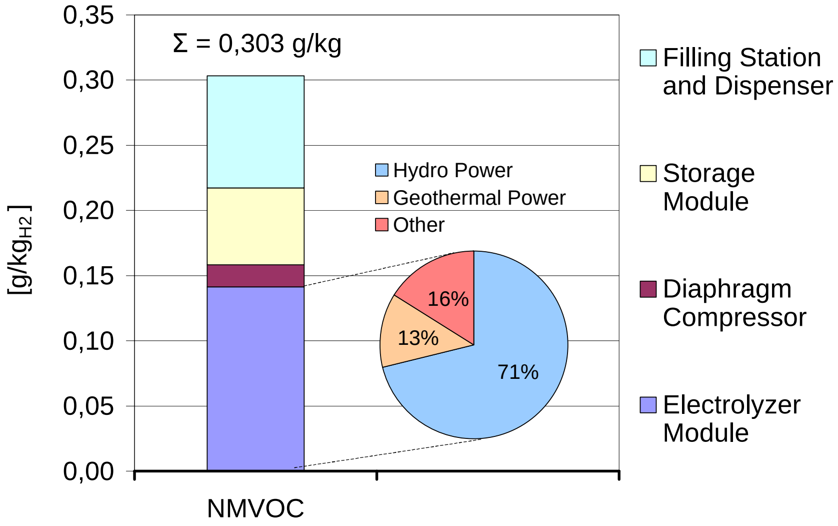

Figure 3-33: NMVOC per kg of on-site H_2 production at the hydrogen station

NMVOC (NON METHANE VOLATILE ORGANIC COMPOUNDS)

The NMVOC emission shows similar tendencies as the one for NO_x. The emission from the manufacturing and utilisation phase are nearly equal. Regarding the manufacturing, they are caused by processes that deal with the production and machining of metals, mainly steel and in this case nickel from the electrolysers electrodes.

3.4.2 LCI results of the Fuel Cell Bus System Reykjavik (Iceland)

The following diagrams show inventory results for fuel cell bus system in Reykjavik, Iceland, based on one driven kilometre. The manufacturing includes the production of a whole fuel cell bus. Basis for the bus operation is a bus lifetime of 12 years with 60 000 km driving performance per year (720 000 km over lifetime) and a consumption of 20,23 kg H_2 per 100 km (average fuel consumption values for all three buses from week test cycles in Reykjavik, 3rd to 6th May 2004). The environmental effects in operation phase are therefore caused per 100 % by hydrogen production in Iceland and the origin of emissions in this phase are described in part for hydrogen production in Iceland. In the end of life phase the fuel cell bus is recycled.

PRIMARY ENERGY DEMAND (PE)

In Figure 3-34 the primary energy demand per driven kilometre is shown. As hydrogen in Iceland is produced from renewable resources, the whole primary energy demand for operation is renewable (hydro power and geothermal power). Almost 97 % of PE is caused by operation. In manufacturing phase the main share of PE is non-renewable (approx. 80 %).

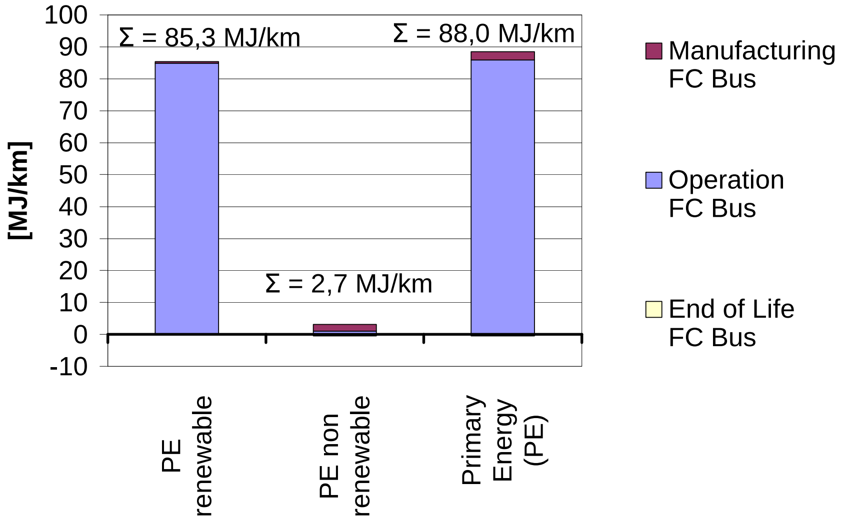

Figure 3-34: Primary Energy per 1 km driven with FC-bus in Iceland

CARBON DIOXIDE (CO_2)

In CO_2 emissions the share of manufacturing (39 %) is much bigger than in primary energy. This is because of the high share of renewable energy sources in Iceland and the relatively low CO_2 emissions related to energy production. In manufacturing phase CO_2 is mainly caused by metal production.

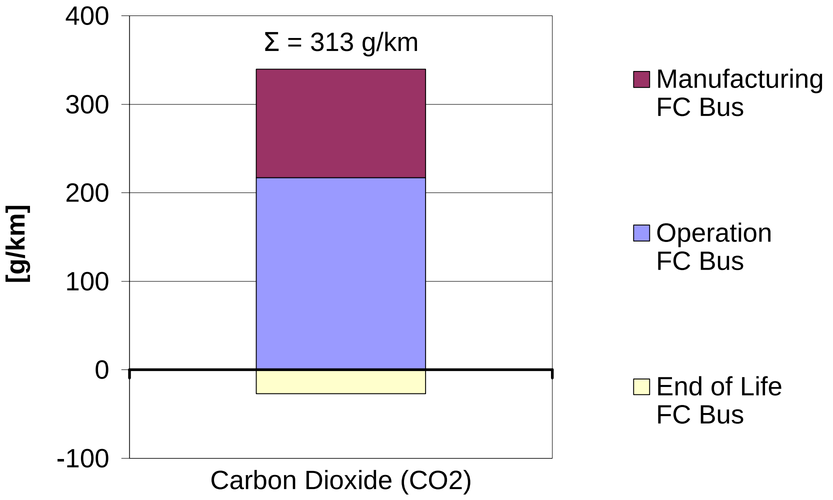

Figure 3-35: CO_2 per driven km

CARBON MONOXIDE (CO)

CO emissions from manufacturing are a little higher than from operation phase and derive with a high share from metal production. In end of life phase these metal components are recycled and credits are given.

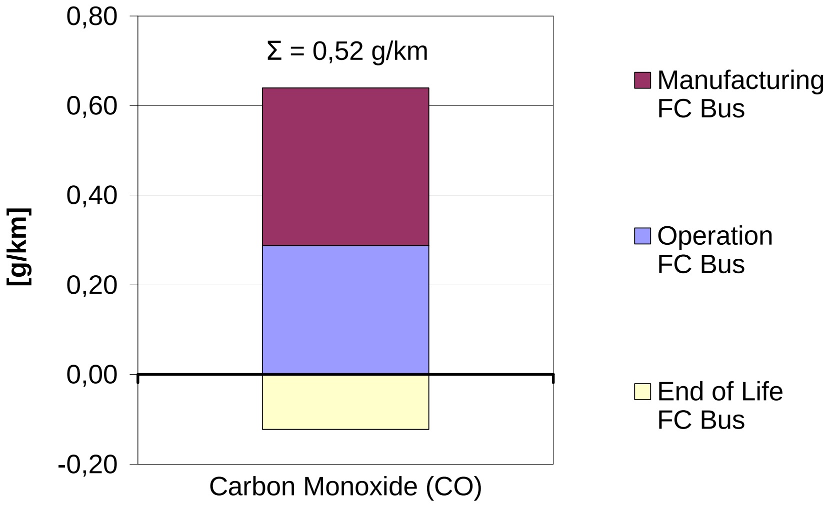

Figure 3-36: CO per driven km

NITROUS OXIDE (N_2O)

In N_2O emissions manufacturing of the bus is dominating. This results from metal production and energy demand in bus components production.

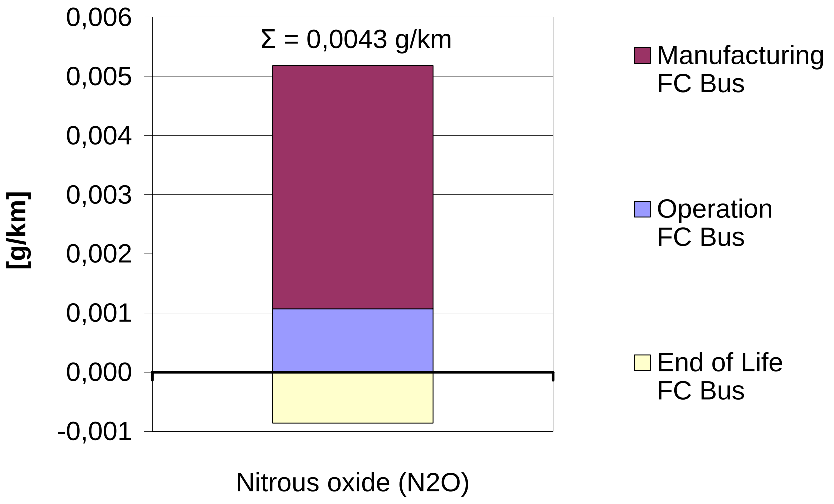

Figure 3-37: N_2O per driven km

SULPHUR DIOXIDE (SO_2)

SO_2emissions in manufacturing phase are almost completely caused by steel production and with end of life recycling of steel components most of these emissions can be credited.

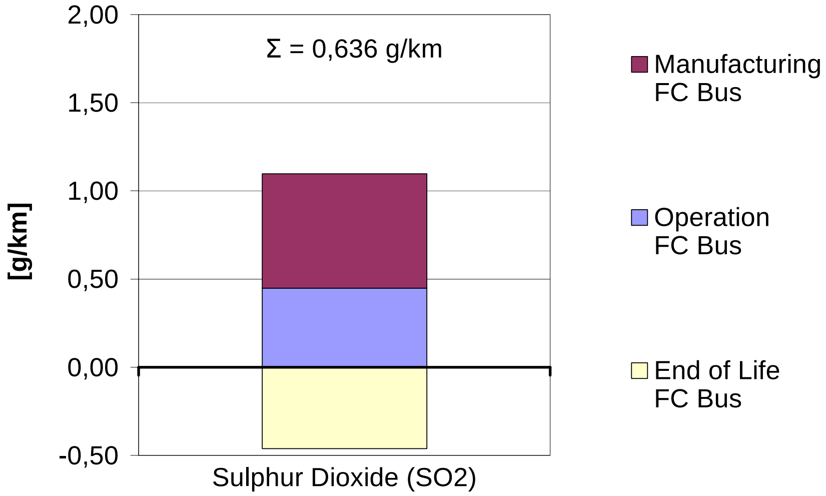

Figure 3-38: SO_2 per driven km

HYDROGEN SULPHIDE (H_2S)

Emissions of H_2S are fully caused by operation phase and there from geothermal power plant. This is related to the special situation in Iceland.

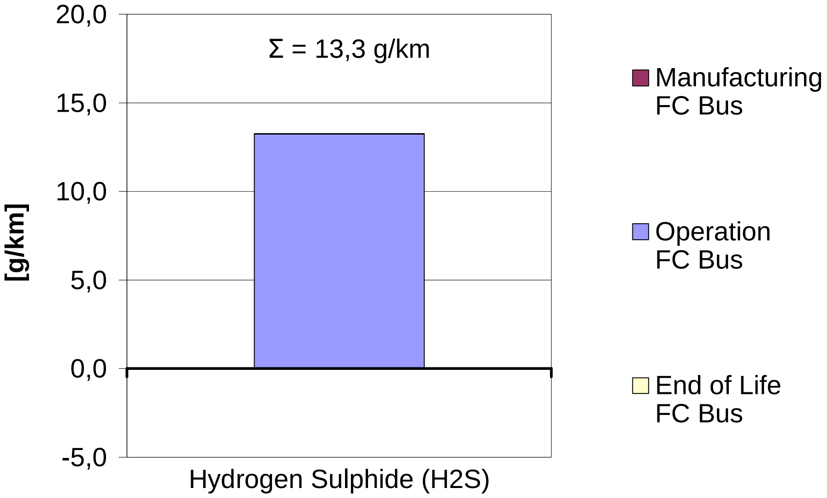

Figure 3-39: H_2S per driven km

METHANE (CH_4)

The figure for methane emissions is almost equal to the one for CO. Emissions of manufacturing are mainly caused by steel production and processing as well as some other materials. Emissions from operation result from Icelandic electricity grid mix (see figure Figure 3-31).

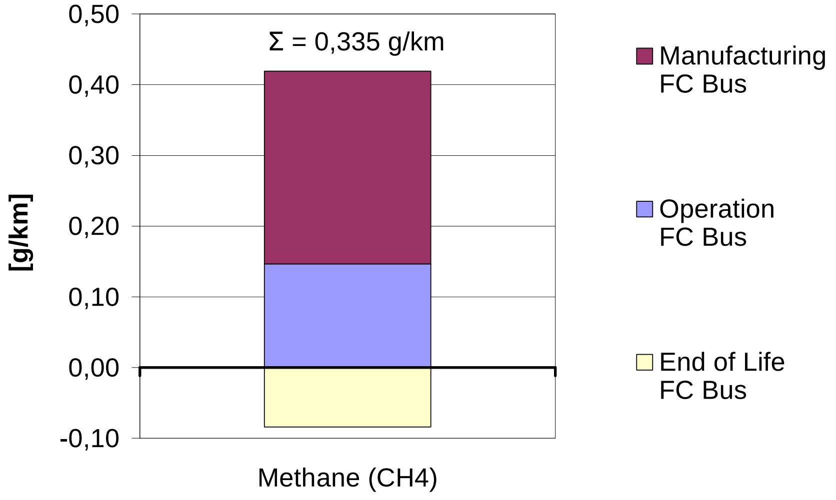

Figure 3-40: CH_4 per driven km

NITROGEN OXIDES (NO_x)

In bus manufacturing phase NO_x emissions has its origin mainly in the steel and other metal production. NO_x is also a typical emission related to the combustion of fossil fuels, e.g. in diesel engines.

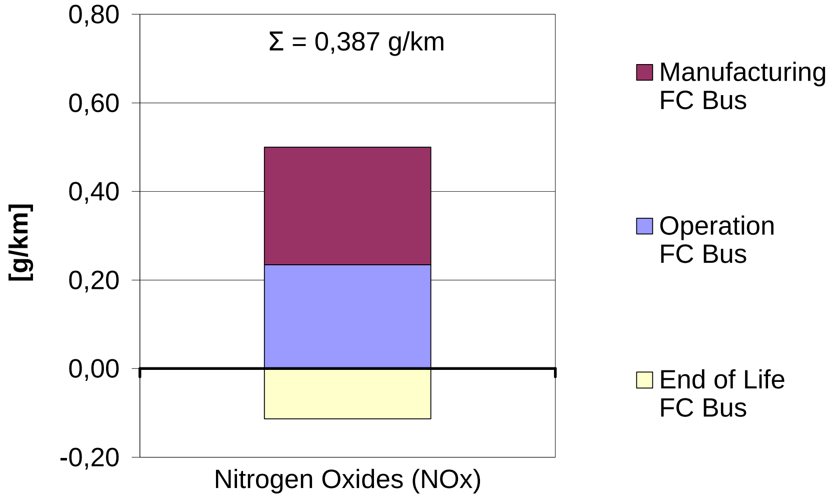

Figure 3-41: NO_x per driven km

NMVOC (NON METHANE VOLATILE ORGANIC COMPOUNDS)

NMVOC emissions in manufacturing are produced by solvent use in processing (e.g. lacquering) and material production.

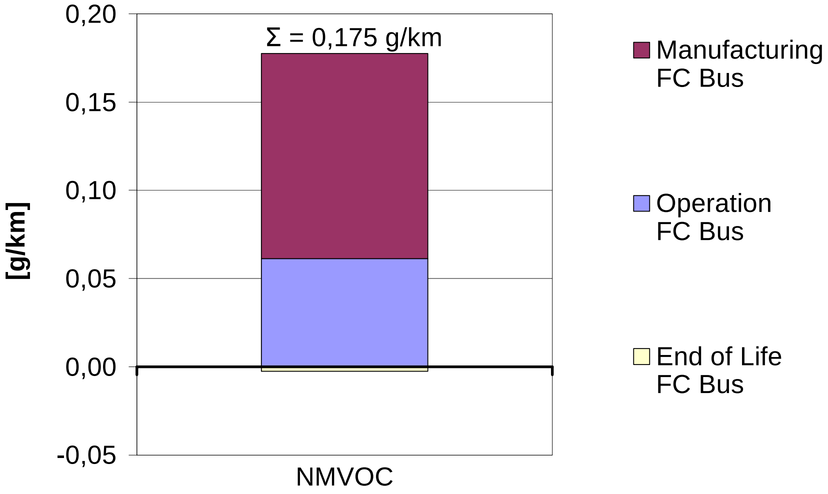

Figure 3-42: NMVOC per driven km

3.4.3 LCI results of the hydrogen production – Electrolyser and Steam Reformer

Within the following chapter, LCI results for different ways of on site hydrogen production will be presented and discussed. Focus of the discussion is to show the influence of the energy source, the location of the production facility and the contribution of the different phases (production of facilities, operation, compression and end of life) to the analysed inventories of 1 kg hydrogen produced on site. As the technology and different scenarios are within the focus, average numbers for the production of the electrolyser and steam reformer module, for energy consumption within operation phase and for compression and an average end of life phase has been considered. The considered boundary conditions for the operation of the electrolyser is shown in Table 3-2 and for the steam reformer in Table 3-4.

	Electrolyser Germany 2001	**Electrolyser Iceland 2001**	**Electrolyser wind land**	**Steam Reformer**
natural gas	------	-----	-----	natural gas; german import mix
power electrolyzer	german grid	icland grid	wind power	-----
power compression	german grid	icland grid	wind power	german grid

Table 3-9: Used fuel / energy supply route[1]

Different technologies for power production and different grid mixes are used within the different scenarios as the source for the needed power to investigate the influence of the power production on the environmental footprint. For a better understanding of the results a dedicated analysis of the emissions and environmental impacts of the Icelandic and German grid mix can be found in Appendix E.

As hydrogen production by steam reformer can be also used for hydrogen production on site, this technology is also discussed. The fuel/ energy supply routes for the different scenarios are shown in Table 3-9. The steam reformer and electrolyser technology is the same for all scenarios. It has to be noted that the onsite electrolysers and especially the onsite steam reformers used in the ECTOS and CUTE project, on which this LCA is based, have to be considered as prototypes and therefore they are not optimised in terms of energy efficiency and emissions from operation. A quantification of the development potentials for these two hydrogen production technologies in the near and medium term will be given in the LCA report for the CUTE project.

The following figures show inventory results for on site production of 1 kg of hydrogen within different boundary conditions as described earlier. The following inventories are discussed:

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[1] The wind turbine is a pitch controlled horizontal axle converter with gearbox and variable speed. It has a rotor diameter of 77m and a hub height of 85 m. It is located inland and has an installed capacity of 1,5 MW, with an annual average wind speed of 5 m/s and an annual production of 1770 MWh (average values for Germany). The wind turbine has an assumed lifetime of 20 years and an efficiency of 40 % [20].

- Primary energy demand,
- Carbon dioxide,
- Carbon monoxide,
- Sulphur dioxide and
- Nitrogen oxides.

The manufacturing of components for the developed infrastructures of natural gas, crude oil and grid electricity supply (platforms, pipelines, power plants etc.) is not included since the production of these components was previously studied [12] and their relevance was found to be negligible per unit of product (e.g. l diesel) in particular due to the high product output of these facilities.

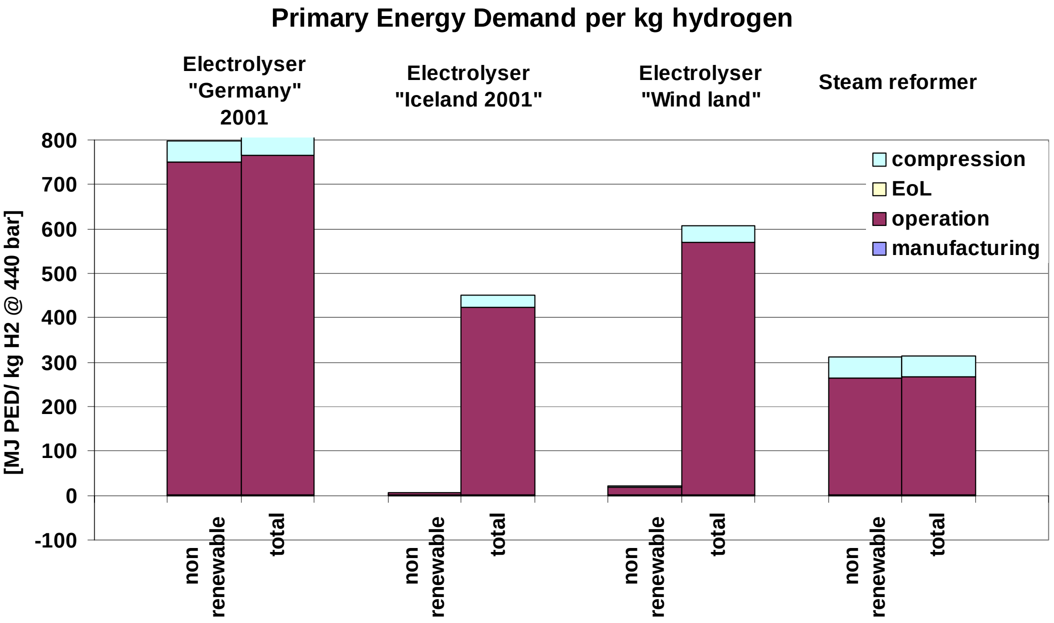

Figure 3-43: Hydrogen production – primary energy demand

The total and non-renewable primary energy demand of the analysed on site hydrogen production routes is shown in

Figure 3-43. The non renewable primary energy demand is an indicator for the resource consumption of the production of a product and the total amount represents the energy intensity of the production. Analysing the total primary energy demand shows that electrolysis using German grid mix has the highest and Steam reformer has the lowest primary energy demand. The ration is approximately 2,5 even though the energy efficiency of the processes (electrolysis and steam reforming) are within the range of +- 5 %. This is based on the fact that the total primary energy demand of 1 MJ electricity (German grid mix) is approximately 3,3 times of the total primary energy demand of the natural gas mix for Germany. However, analysing the non-renewable primary energy demand gives a representative picture regarding the consumption of limited resources. It clearly shows the potential of resource conservation of electrolysis compared to steam reforming when using either wind power or the Icelandic grid mix. For more detailed information on the Icelandic and German grid mix, please see chapters 3.2.3 and 3.2.4.

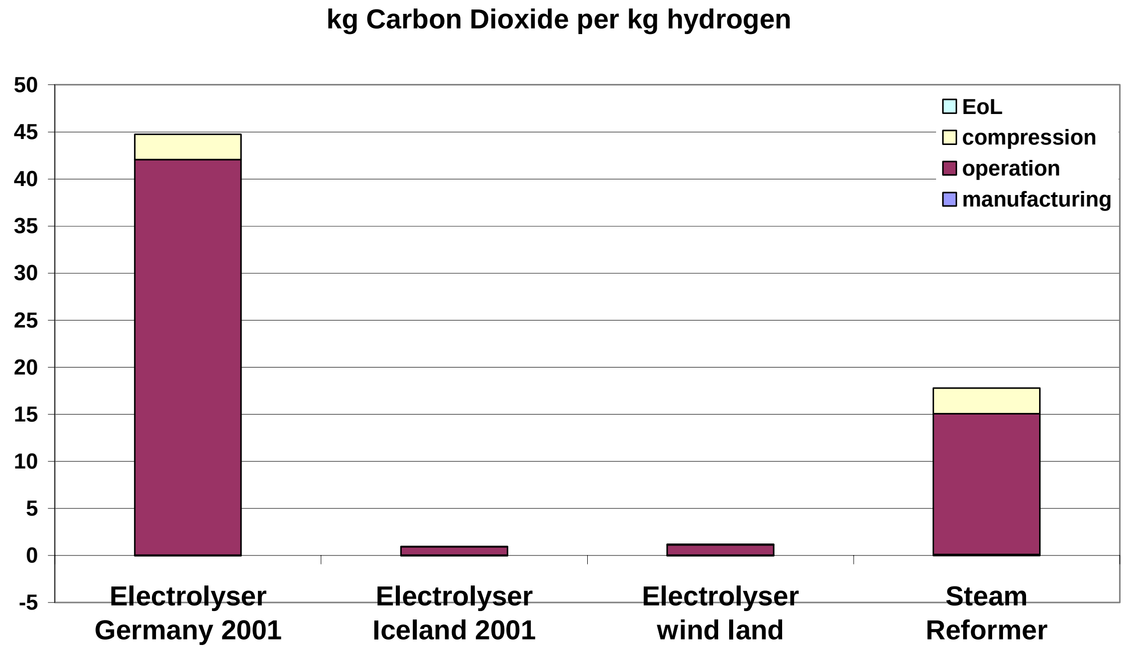

Figure 3-44: H_2 production – CO_2 emissions

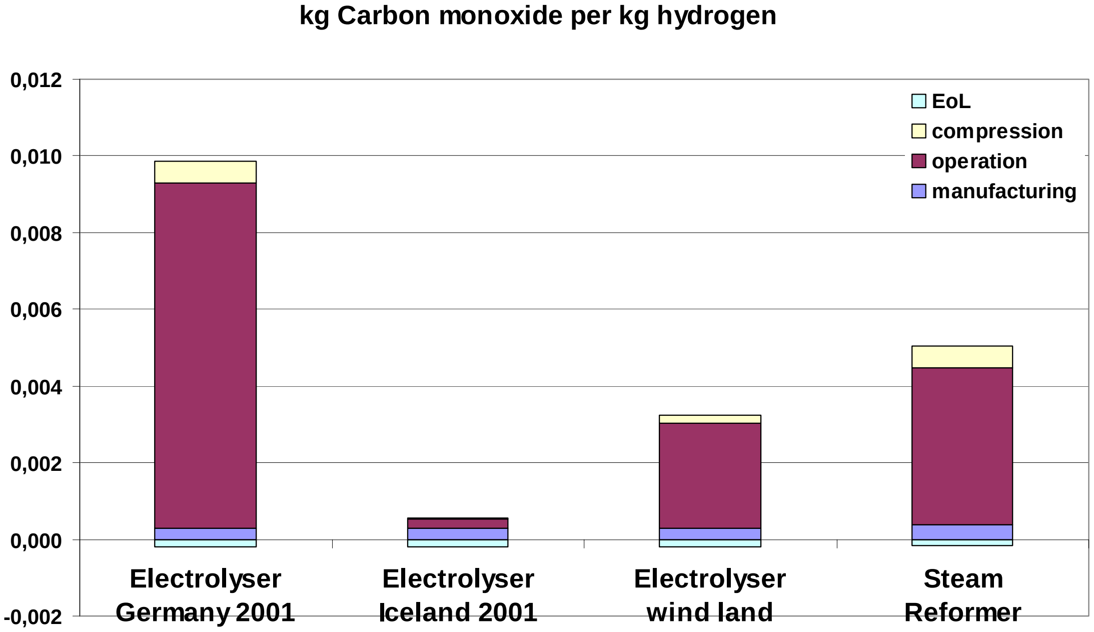

Figure 3-45: H_2 production – CO emissions

The CO_2 emissions for hydrogen production by electrolysis are dominated (> 90 %) by the power consumption (stack and compression) while in case of steam reforming approximately 35 % of the CO_2 emissions are related to power consumption (compression and utilities) and approximately 60 % are direct emissions of the reforming process. As illustrated in Figure 3-45 the amount of CO emissions for the operation of the electrolyser using wind energy is of significance. These CO emissions are mainly related to the metal production (>70 %) for the metal content of the windmill.

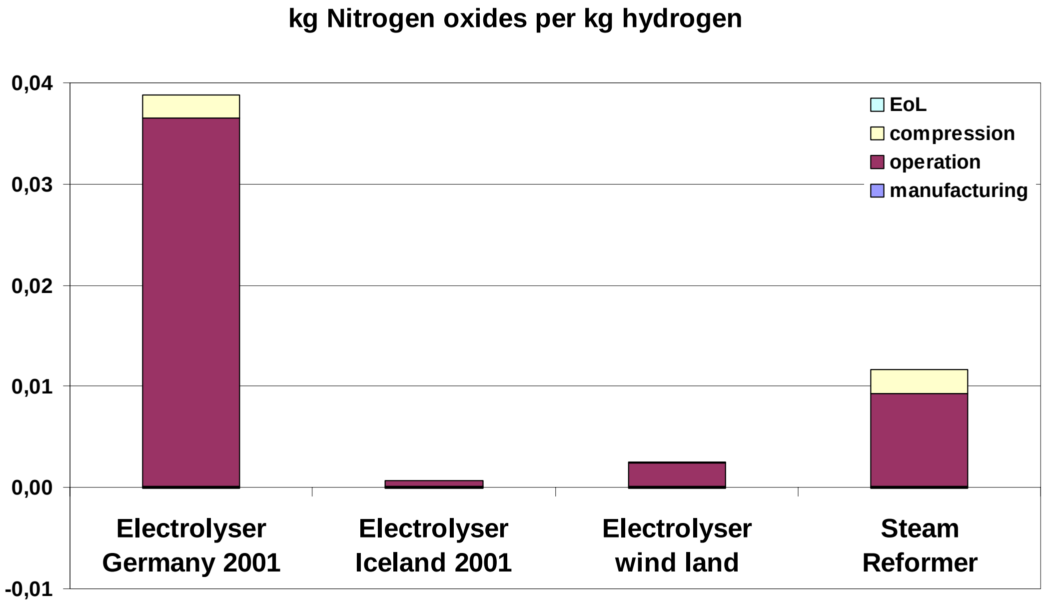

Figure 3-46: H_2 production – NO_x emissions

Figure 3-47: H_2 production – SO_2 emissions

As presented in Figure 3-46 and Figure 3-47 the electrolysis using renewable energy source show advantages compared to electrolysis using mainly coal and oil for electricity production and steam reforming using natural gas. While the share of the natural gas supply to the CO_2, CO and NO_X emissions is < 20 %, the share to SO_2 emissions is approximately 35 %. The dominating source for NO_X and SO_2 emissions is the power consumption for compression and utilities for steam reforming and for compression and the stack for electrolysis.

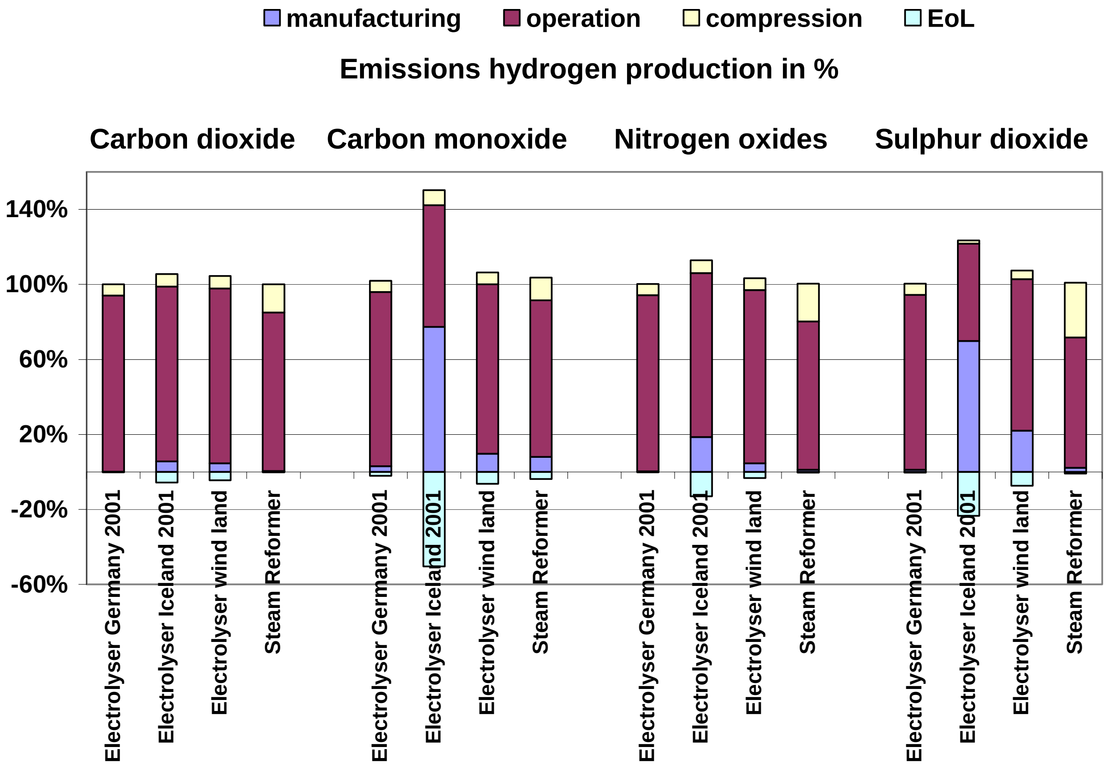

Figure 3-48: Hydrogen production – Emissions

Looking at the relative distribution of the emissions between the four life cycle phases, it can be seen that the manufacturing phase becomes more relevant when renewable resources are used, keeping in mind that the absolute emission values go down. Its share goes up to over 50 % for the electrolysis route using Icelandic power for selected emissions. As the contribution (shares) of the different life cycle phase to the overall emissions vary significantly when analysing different emissions, as shown in Figure 3-48, it is important to include the total life cycle.

3.4.4 LCI results of the bus manufacturing

Figure 3-49 states the overall primary energy demand for the manufacturing of the 3 bus versions. The share of FC system accounts for ~ 59 %. The relevance of the fuel storage system is mainly related to the used carbon fibres (applies also on fuel storage system for CNG bus). For the FC stack platinum is the most relevant contributor to the primary energy demand. The used platinum is based on the current world mix of platinum with 80 % primary material and 20 % recycled platinum, mainly from the recycling of automotive catalysts [27]. The share of renewable primary energy accounts for 18 % for the FC bus and 5 % for the CNG and diesel version. The increased share for the FC bus can be explained with the fact that the electricity grid mix of the state of British Columbia, where the FC system is manufactured, is based to more than 95 % on hydro power.

The distribution of shares of the different component groups for emissions stays more or less stable, the supply of platinum with its high energy/ electricity demand dominates the FC system for each emission (see Figure 5-3 in the Appendix C). For hydrocarbons measured as volatile organic compound (VOC) the situation is some what different (see Figure 3-50). The painting of the bus is of special relevance. The used cataphoretic painting, primer, filler and coating paint are all based on solvents. These solvents evaporate during paint application even though a large portion is caught by thermal after treatment, leading to the high share of VOC emissions.

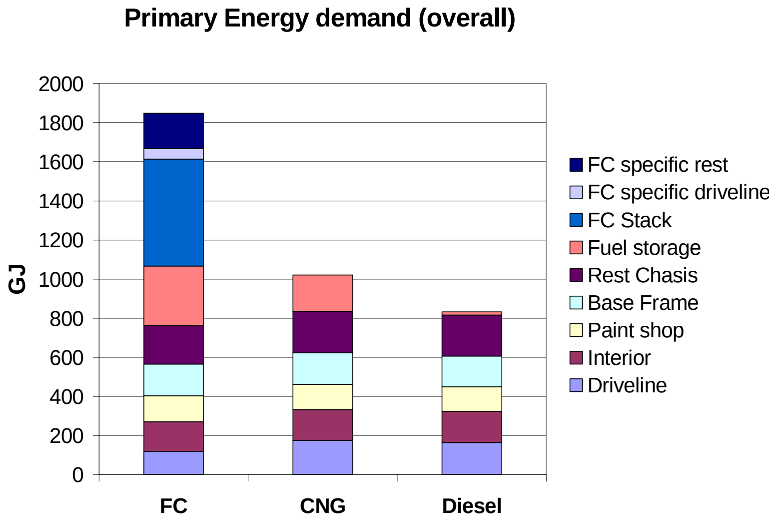

Figure 3-49: Primary energy demand

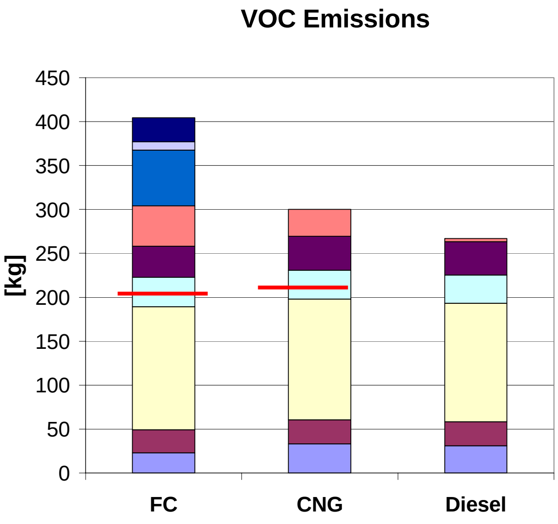

Figure 3-50: Volatile organic compounds (VOC) emissions

3.4.5 LCI results of the bus system comparison

ASSUMPTIONS:

For the system comparison of FC, CNG and diesel buses the following assumption were made: lifetime 12 years, yearly mileage 60.000 km, resulting in 720.000 km lifetime mileage. The buses are operated on the Line 42 and Esslingen routes using the consumption and emission values as presented in chapter 3.4.3. Maintenance of the buses is not included. The following fuel supply routes are considered:

Fuel	Supply route
Hydrogen	Production via on site steam reformer (see chapter 3.2.5), German natural gas (see chapter 3.2.7), German power grid mix (see chapter 3.2.4)
	Production via on site electrolyser, power from wind power (located inland) (see chapter 3.2.2)
Natural gas	German natural gas mix, German power grid mix, stored onboard at 200bar (see chapter 3.2.7)
Diesel	German crude oil mix, German refinery, 10 ppm sulphur content (see chapter 3.2.6)

Table 3-10: Considered fuel supply routes

RESULTS:

The advantage of hydrogen produced from renewable resources (in this case wind power) can seen comparing Figure 3-51 and Figure 3-52. In Figure 3-51 the hydrogen from wind power route has the highest value, looking at the primary energy demand from non renewable resources the route features the lowest values (only 3 % of the overall primary energy demand of the hydrogen from wind power route are from non renewable resources). From the perspective of sustainability the primary energy demand from non renewable is more meaningful since it reflects the consumption of depleting natural energy resources. The FC bus using hydrogen from natural gas with its current consumption does not offer advantages in terms of energy efficiency compared to CNG and diesel buses. Around 30 % of the primary energy demand is related to the electricity consumed by the steam reformer and compressor. At which fuel consumption an energetic break even of the FC bus with its conventional competitors is reached is analysed in chapter 3.2.8. The relation between the different systems on both routes is comparable with the diesel bus showing the lowest energy demand and a larger difference between diesel and CNG on the less demanding Esslingen cycle.

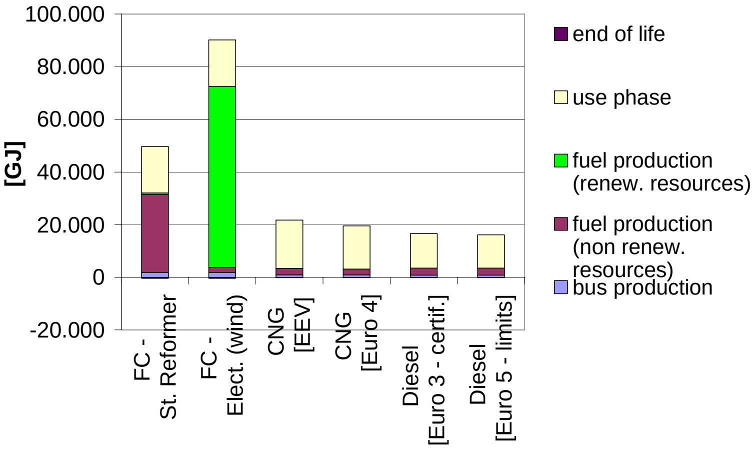

Figure 3-51: Primary energy demand (overall) Line 42

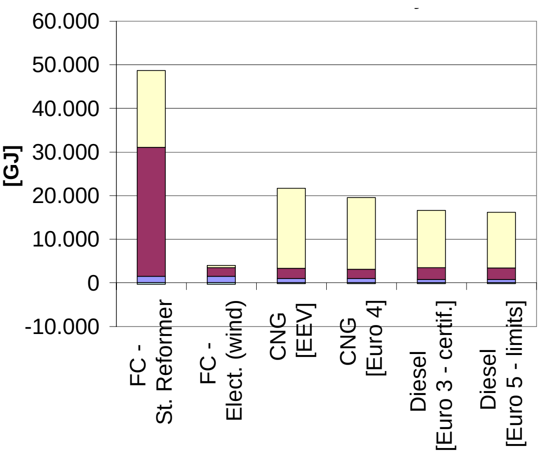

Figure 3-52: Primary energy demand (non renewable resources) Line 42

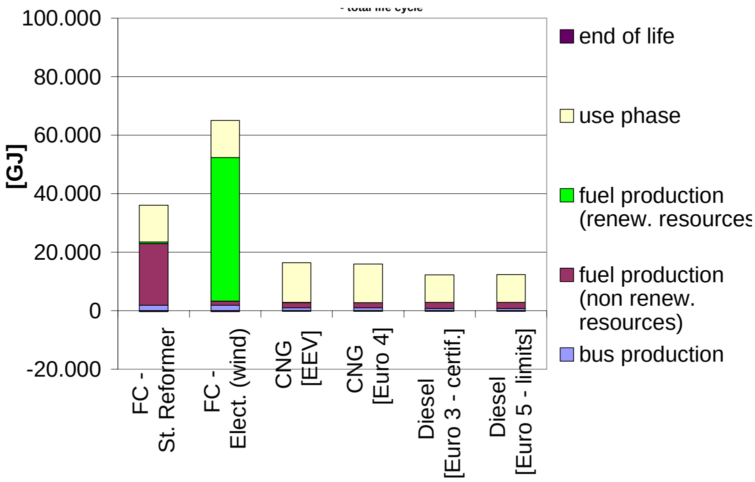

Figure 3-53: Primary energy demand (overall) Esslingen cycle

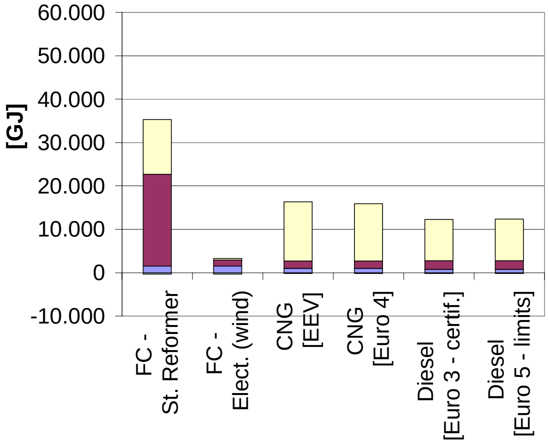

Figure 3-54: Primary energy demand (non renewable resources) Esslingen cycle

Analogue to the primary energy demand from non renewable resources the FC bus using hydrogen from wind power demonstrates its potential to mitigate CO_2 emissions. Around one third of the CO_2 emissions of the FC bus using hydrogen from steam reforming of natural gas stem from the consumed electricity used for the steam reformer and compression. With a CO_2 factor of 1,992 kg/ Nm³ natural gas diesel and CNG show comparable CO_2 emissions throughout the systems life cycle. For Diesel Euro 5 a 3 % reduction in consumption is assumed. The required urea solution for the necessary SCR system is included (5 % of fuel consumption), it accounts for around 2 % of the life cycle emissions.

Looking at the NO_X emissions the FC bus shows again its advantages. Applying Diesel Euro 5 certification values CNG looses its previously observed superiority in terms of NO_X emissions even if EEV standard is considered.

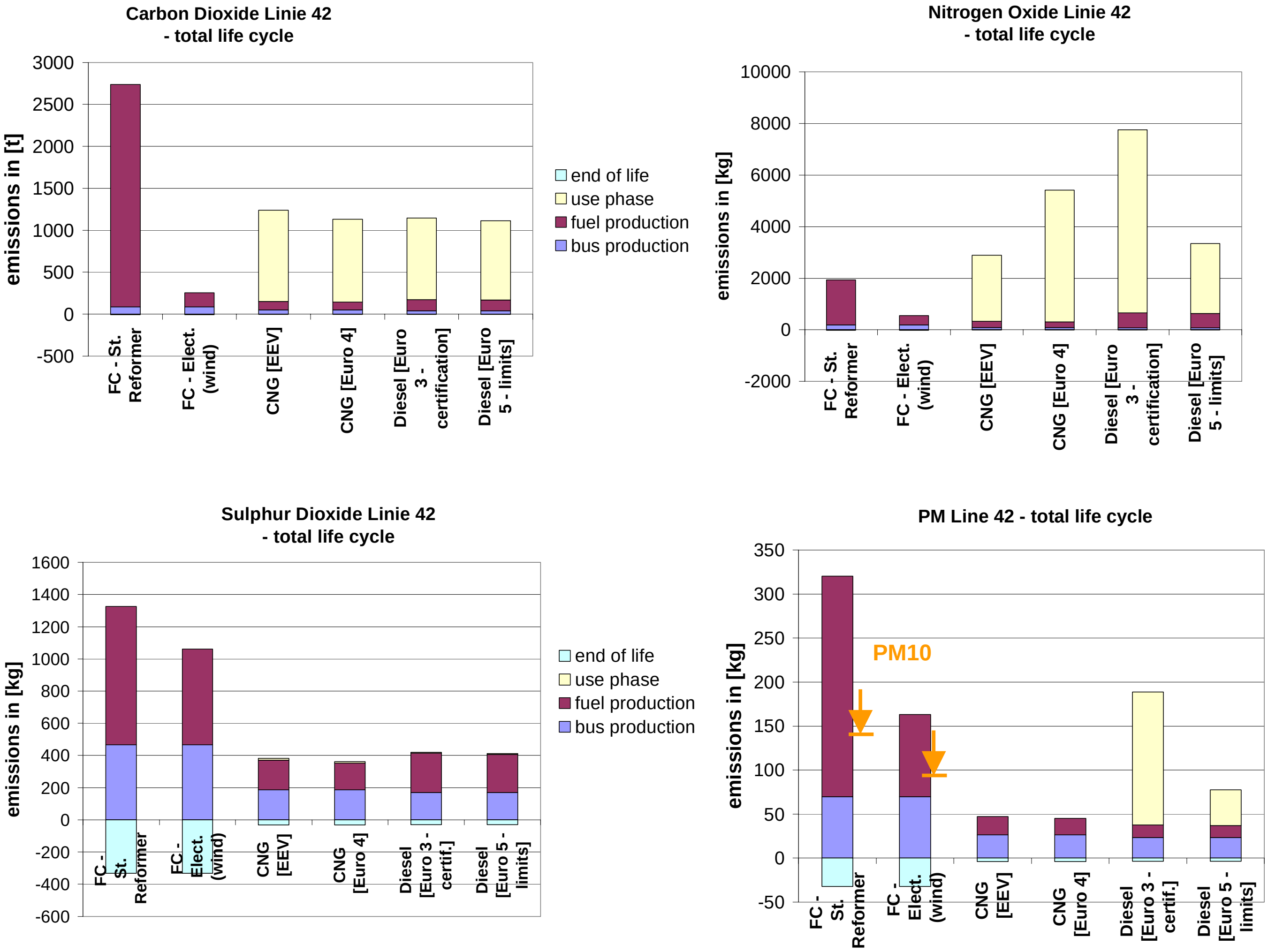

Figure 3-55: Emissions to air – Line 42

The carbon monoxide emissions (Line 42 – total life cycle) are listed in Figure 5-4 in Appendix C.

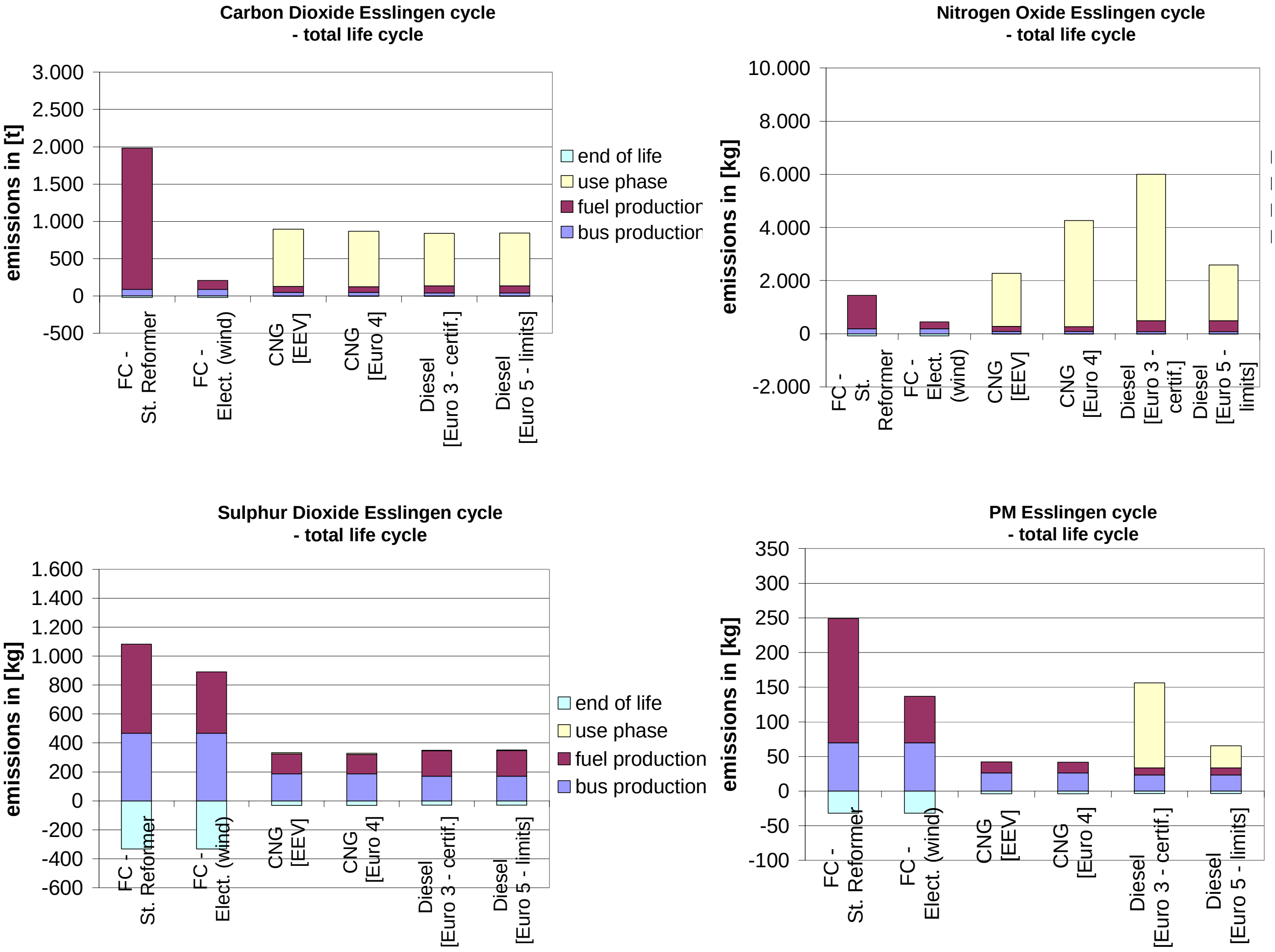

Figure 3-56: Emissions to air – Esslingen cycle

The carbon monoxide emissions (Esslingen cycle – total life cycle) are listed in Figure 5-5 in Appendix C.

Due to the as sulphur free considered diesel fuel and the natural gas with a similar minimal sulphur content the operation phase has no relevance for the life cycle SO_2 emissions. The FC bus has a twofold disadvantage. The first one stems from the higher SO_2 emissions during bus manufacturing mainly caused by the precious metal demand. The second one depends on the hydrogen supply route. For the steam reformer route it originates to ~40 % in the electricity consumed by the steam reformer and during compression. Another 20 % are related to the natural gas supply. For the electrolyser route using wind power the SO_2 emissions result from the manufacturing of the wind turbine and to a reduced degree from the manufacturing of the electrolyser. According to the applied methodology the recycling of platinum used as catalyst in fuel cell results in credits for replacing virgin platinum material[1] which reduce the SO_2 life cycle emissions of the FC bus system.

The aggregated particulate matter (PM) figure shows also disadvantages for the FC bus. Due to data availability issues it could not be distinguished between the as noxious considered PM smaller than 10 µm and the as harmless considered mineral dust larger than 10 µm. Estimating the share of PM10 of the FC bus life cycle at a maximum of 40 % and considering the fact that all PM emissions of the diesel bus operation are smaller than 10 µm then the situation regarding PM looks somewhat different bringing the FC bus in a better position compared to the diesel bus. Because of almost no PM emissions in the operation phase the CNG bus has the lowest PM life cycle emissions. In correlation to the SO_2 emissions the platinum recycling leads to relevant PM credits. The PM as well as the SO_2 emissions are related to the supply of electricity, which is heavily consumed during beneficiation and processing, in the PGM producing countries (mainly South Africa).

The comparison of the emissions across different routes based on certification is at this point of little explanatory power. A detailed comparison will be done when the emissions from the measurements in Graz will be available.

A comparison of diesel and FC bus on the basis of primary energy demand and CO_2 emissions on the route No.3 in Reykjavik can be found in the well to wheel report of the ECTOS Project (D15). It uses the LCI data for the project specific hydrogen supply and Iceland specific diesel supply. The data was calculated using the same approach as described in the report at hand.

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[1] According to the current (2003) world mix of Platinum a share of 80 % virgin material is assumed, i.e. the credits are calculated for 80 % of the incorporated platinum weight including all efforts (energy/ material consumption, emissions) made during the recycling process

4 Life Cycle Impact Assessment (LCIA)

The impact assessment is carried out on the basis of the inventory analysis data. These data are categorised according to their potential impact on the environment in impact categories. These categories describe the potential environmental impacts rather than the actual effects.

4.1 Methodology

The standard ISO 14042 divides the phases of the impact assessment into mandatory (chapter 4.1.1, 4.1.2, 4.1.3) and optional elements (chapter 4.1.4, 4.2.6). In this study only the mandatory elements are considered. For more information and background knowledge about the proceeding, see [24].

4.1.1 Selection of Impact categories

The following table (Table 4-1) shows the selected impact categories. The reasons for this selection are discussed in [24].

Impact category/ aggregated inventory data	***Unit***[1]	***Short description***	***Examples***
Global warming potential (GWP)	kg CO_2 equivalent	Emissions to air which influence the temperature of the atmosphere	CO_2, CH_4 ....
Acidification potential (AP)	kg SO_2 equivalent	Emissions to air and soil which cause acidification of rain, soil and water	NO_X, SO_2, HCl, HF ....
Eutrophication potential (EP)	kg Posphate equivalent	Eutrophication of lakes, rivers and soil	P and N compounds
Photochemical ozone creation potential (POCP)	kg Ethene equivalent	Emissions to air which lead to ozone production in the troposphere	Hydrocarbons

Table 4-1: Selected impact categories which assess environmental impact

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[1] characterisation factors are given in Appendix F

4.1.2 Assignment of LCI results (classification)

In the classification step the inventory data is assigned to categories according to their impact. For instance, carbon dioxide emissions contribute to the greenhouse effect.

4.1.3 Calculation of Category indicator results (characterization)

Every substance is assigned to a potential impact in the impact category under study. The potential impact of a substance is set in relation to a dominant factor in the category. The characterisation factors for the selected impact categories are given in Appendix F

4.1.4 Optional methodological elements in LCIA

NORMALISATION

The Normalisation is an optional element in LCIA. It sets the contribution of a product system in relation to the overall environmental impacts of e.g. a country or continent. In this way, the significance of the contribution of a product assigned to an impact category can be shown. This, however, does not provide any assertions on whether one impact category is more important than the other from an ecological point of view. For Iceland there were no normalisation factors available. This is a field where further research is required. However an exemplary normalisation was carried out for the hydrogen production taking Europe as reference (see chapter XX). For the overall system there was no normalisation carried out.

GROUPING

The Grouping, as an optional element in LCIA, isn’t implemented separately in this study. A division into groups e.g. categorizing the environmental impacts into local, regional and global groups is not carried out separately since it can be done on the basis of the given results by simply assigning GWP to global, AP and EP to regional and POCP to local impacts with no further consequence to the results. A grouping due to a (subjective) order of significance was determined as inappropriate for this project. For further information see ECTOS methodology report [24].

WEIGHTING

The Weighting aims at an aggregation of impact categories which is establishes a non objective prioritisation of impact categories. Since the weighting keys to be used are widely discussed in the scientific community and taking into account the fact that several impact categories are still in the development stages, the weighting as an optional element in LCIA is not considered in this study.

4.2 LCIA Results

In this chapter life cycle impact assessment results for hydrogen production in Iceland, for the fuel cell bus system in Reykjavik, for general hydrogen production alternatives (electrolysis and steam reforming with European boundary conditions), for the bus manufacturing and for the bus system comparison are shown.

4.2.1 LCIA results of the hydrogen production in Iceland

In general the following diagrams show environmental impacts as proportions and in quantified columns related to 1 kg of produced hydrogen in Iceland. The parts of the hydrogen station (filling station foundation and dispenser unit / diaphragm compressor / storage module / electrolyser module) each include manufacturing, operation and end of life phase. The electricity grid mix for Iceland is used as input during the operation of the electrolyser. These upstream processes are included in the column section electrolyser module and the share related to hydro power, geothermal power and others (electrolyser module manufacturing, operation and end of life) are shown as percentage in the pie chart.

GLOBAL WARMING POTENTIAL (GWP)

Global warming potential (GWP 100 years) is dominated by emissions related to the electricity demand respective the electricity production for the operation of the hydrogen station (mainly power demand for electrolyser module and compressor). CO_2 and CH_4 from hydro and geothermal power generation have the main share on the GWP that is given in CO_2 equivalents.

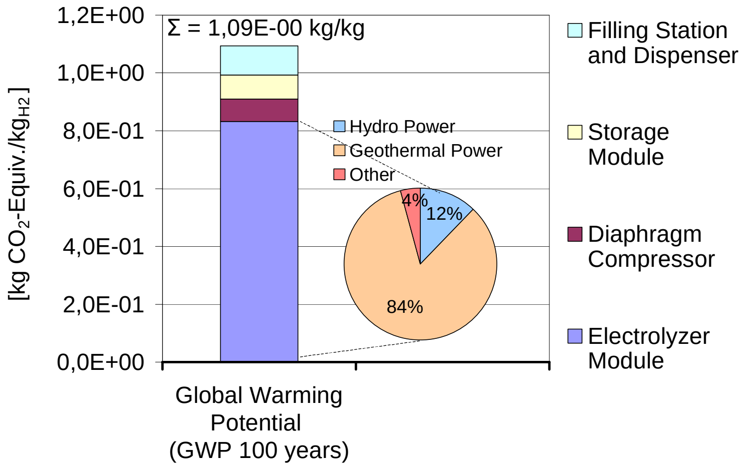


Figure 4-1: GWP per kg H_2 in Iceland

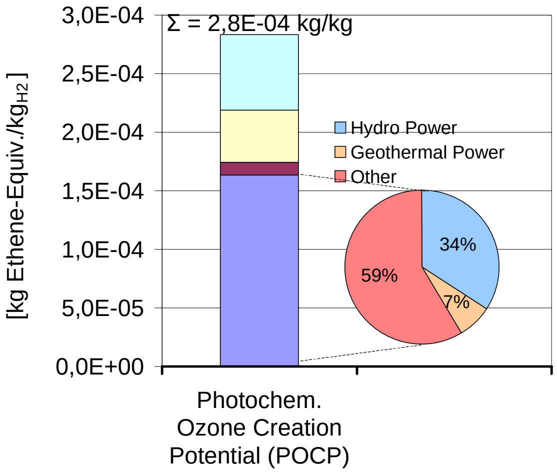


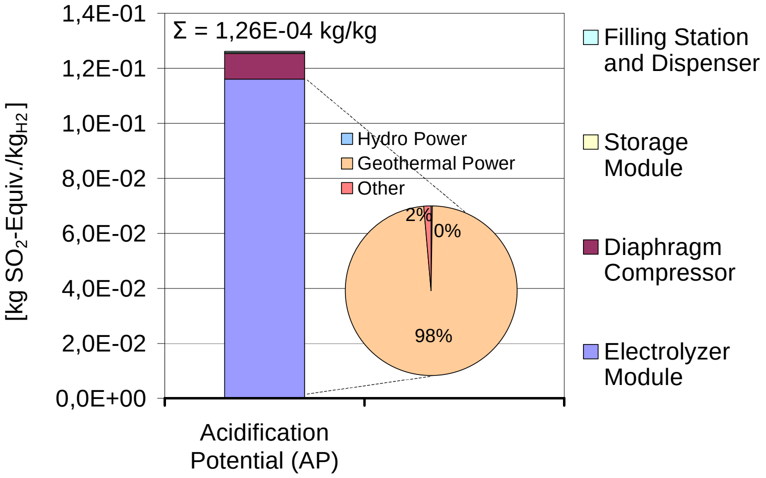
Figure 4-2: POCP per kg H_2 in Iceland

PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP)

POCP is mainly caused by SO_2 and CO emissions from steel and other material production in manufacturing of infrastructure facilities as well as NO_x and NMVOC emissions from transport processes and material production.

ACIDIFICATION POTENTIAL (AP)

The AP measured in kg SO_2 equivalent is almost completely related to the electricity demand for the H_2 production. The main contribution derives from the H_2S emissions within the geothermal power plant. As discussed in the LCI results (chapter 3.4) this is a special situation in Iceland.



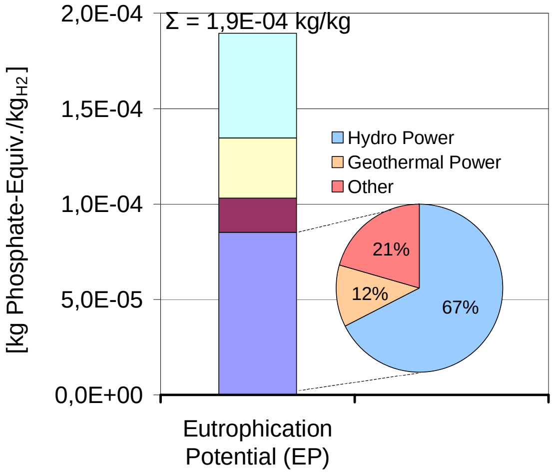


Figure 4-3: **AP per kg H_2 in Iceland**

Figure 4-4: **EP per kg H_2 in Iceland**

EUTROPHICATION POTENTIAL (EP)

Almost 80 % of EP is caused by NO_X emissions to air and almost 20 % by emissions causing COD in water. Main COD results of steel production and main NO_x emissions are related to transportation as well as material production chains (steel and concrete).

4.2.2 LCIA results of the Fuel Cell Bus System Reykjavik (Iceland)

The following diagrams show environmental impact results for fuel cell bus system in Reykjavik, Iceland, based on one driven kilometre. The manufacturing includes the production of a whole fuel cell bus in Germany (bus chasis) and Canada (FC drive train). Basis for the bus operation is an assumed bus lifetime of 12 years[1] with 60 000 km driving performance per year (720 000 km over lifetime) and a consumption of 20,23 kg H_2 per 100 km (value from test cycles in Reykjavik). The environmental effects in operation phase are therefore caused per 100 % by hydrogen production in Iceland and the origin of emissions in this phase are described in part for hydrogen production in Iceland. In the end of life phase the fuel cell bus is recycled.

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[1] Note: This generation of FC buses used in ECTOS and CUTE are prototype buses, which are designed to be operated for a period of 2 years. However to be able to compare it to standard series produced Diesel and CNG buses later on in chapter 3.4.4 and 3.4.5 the lifetime of all buses is assumed to be the same (12 years). This also considers the necessity for FC buses to have a comparable lifetime than conventional buses in order be competitive.

GLOBAL WARMING POTENTIAL (GWP)

Main contributors to GWP are CO_2 and CH_4 and so this impact result of the same reasons as CO_2 and CH_4 emissions: energy and material (steel) production. GWP from manufacturing phase is not very much lower than from operation phase and so it is for Icelandic boundary conditions very relevant to consider it.

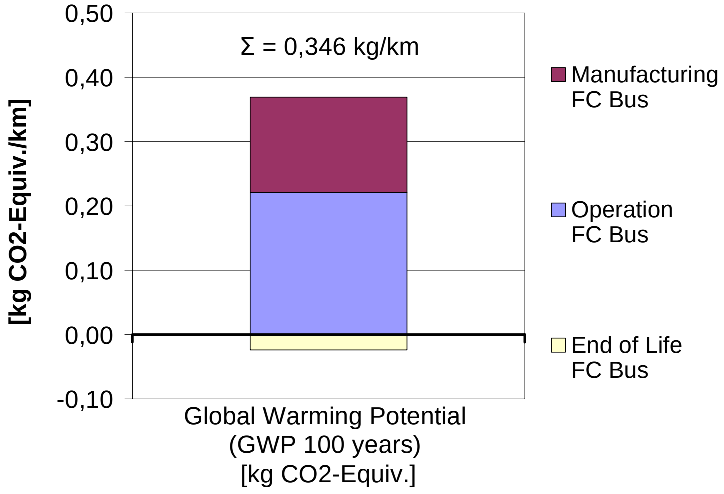


Figure 4-5: GWP per km driven in Iceland

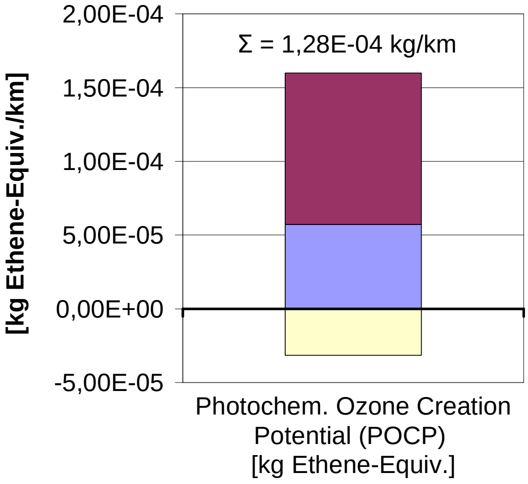


Figure 4-6: POCP per km driven in Iceland

PHOTOCHEMICAL OZONE CREATION POTENTIAL (POCP)

For POCP the round emission origins are: 11 % CO, 24 % SO_2, 8 % NO_x, 57 % VOC (thereof less than 3 % Methane). A very high share results of manufacturing with material production and processing as the main contributors.

ACIDIFICATION POTENTIAL (AP)

AP is mainly caused by H_2S related to electricity production via geothermal power plant in operation phase and only very small contribution of SO_2 and a little NO_x emissions from bus manufacturing.

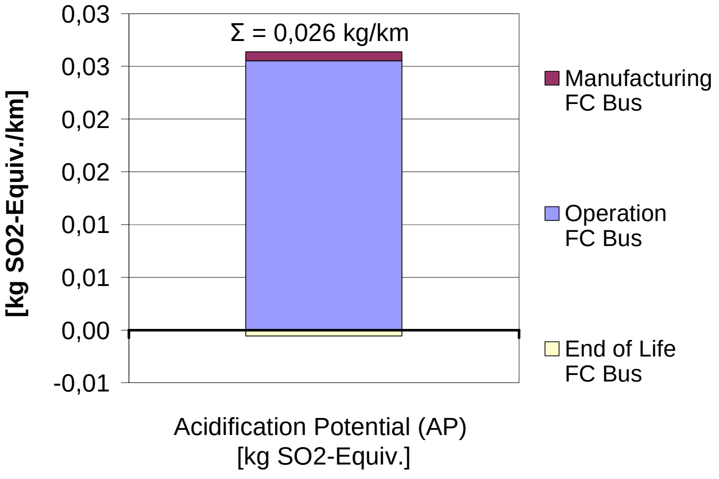


Figure 4-7: AP per km driven in Iceland

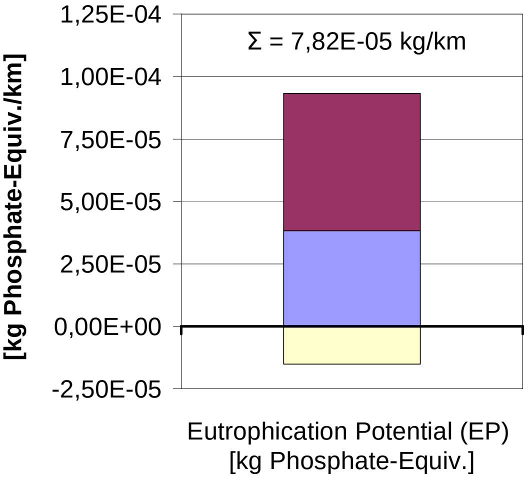


Figure 4-8: EP per km driven in Iceland

EUTROPHICATION POTENTIAL (EP)

Almost 65 % of EP is caused by NO_x emissions to air and almost 35 % by emissions causing chemical oxygen demand (COD) in water. Main COD results from sewage water of steel production and main NO_x emissions are related to transportation as well as material production chains (e.g. steel).

4.2.3 LCIA results of the hydrogen production – Electrolyser and Steam Reformer

Within the following chapter, LCIA results for different ways of on site hydrogen production will be presented and discussed. The discussion focuses on the influence of the energy source, the location of the production facility and the contribution of the different phases (production of facilities, operation, compression and end of life) to the overall impact of 1 kg hydrogen produced on site. Average numbers for the production of the electrolyser and steam reformer module, for energy consumption within operation phase and for compression and an average end of life phase has been considered. The boundary conditions for the operation of the electrolyser is shown in Table 3-2 and for the steam reformer in Table 3-4, the fuel/ energy supply routes for the different scenarios in Table 3-9.

Within the following figures results for on site production of 1 kg of hydrogen of the following impact categories are presented:

- Global Warming Potential (GWP),
- Photochemical Ozone Creation Potential (POCP),

- Acidification Potential (AP) and
- Eutrophication Potential (EP).

For more detailed information on the impact categories, please see the methodology report.

The manufacturing of components for the developed infrastructures of natural gas, crude oil and grid electricity supply (platforms, pipelines, power plants etc.) is not included since the production of these components was previously studied [12] and their relevance was found to be negligible per unit of product (e.g. l diesel) in particular due to the high product output of these facilities.

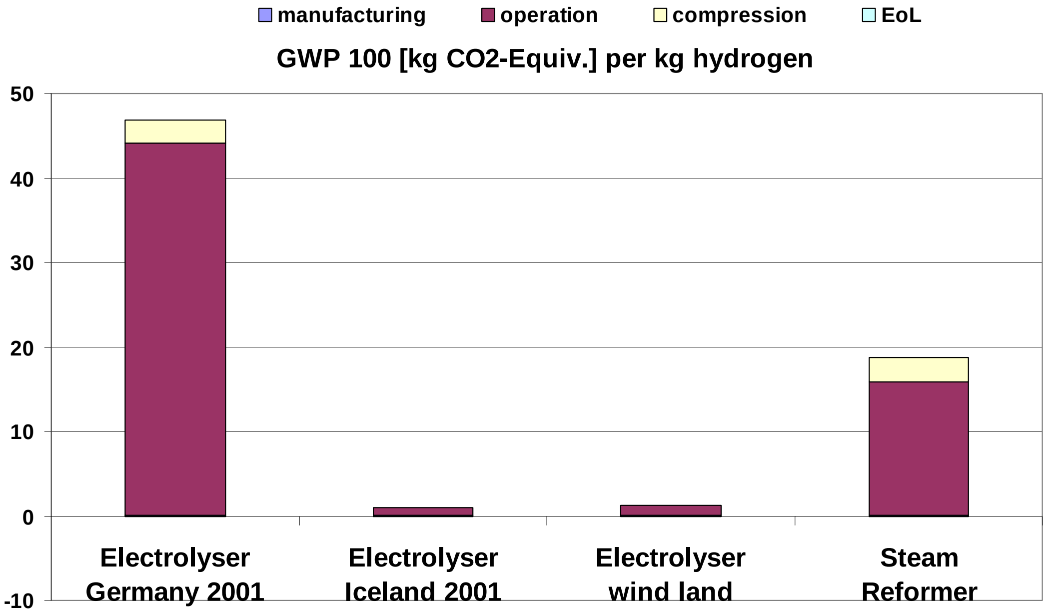


Figure 4-9: Hydrogen production – Global Warming Potential (GWP)

The results for GWP, as shown in Figure 4-9, have similar characteristics as the non-renewable primary energy demand, shown in Figure 3-43 and the CO_2 emissions, see Figure 3-44. This is due to the fact, that the CO_2 emissions are dominating the GWP and they are mainly related to the energy conversion process (production of electricity/ steam reforming) of non-renewable energy resources. The main difference between the electrolysis and the steam reforming process is that the CO_2 emissions for electrolysis are "indirect" while at steam reforming they are direct emissions. Therefore as the operation phase is the dominating phase, the GWP is directly related to the energy source.

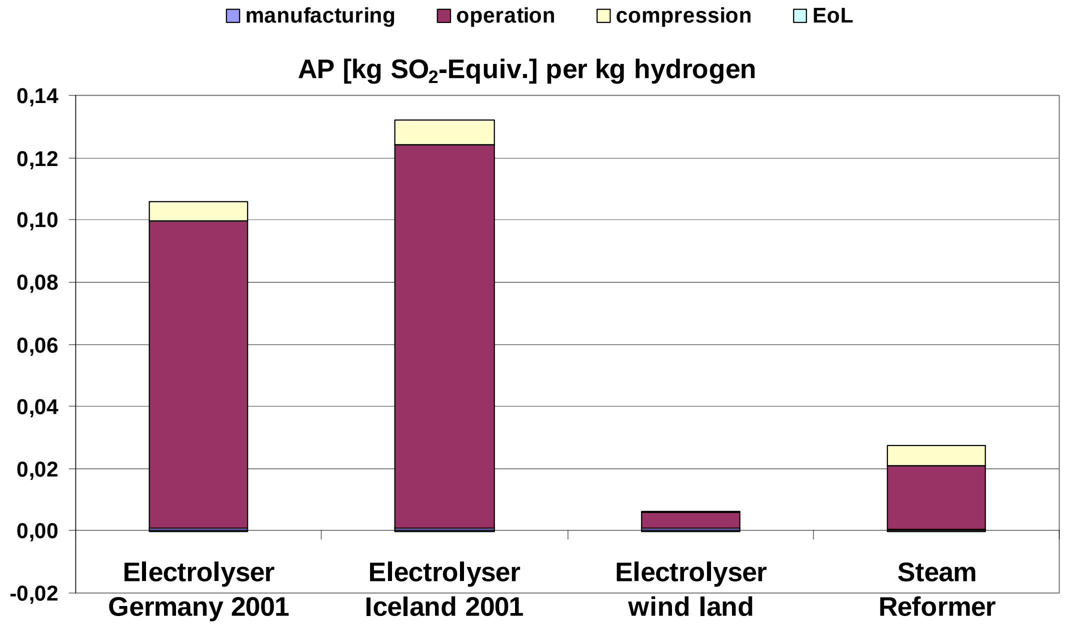


Figure 4-10: Hydrogen production – Acidification Potential (AP)

The acidification potential is the only impact category, which show a different ranking than the other analysed impact categories. As shown in Figure 4-10, the hydrogen production by electrolyser using the Icelandic grid mix has the highest acidification potential. This is related to the H_2S emissions; which is responsible for approximately 99 % of the AP, from geothermal energy production. For more detailed analysis, please see chapter 3.2.3.

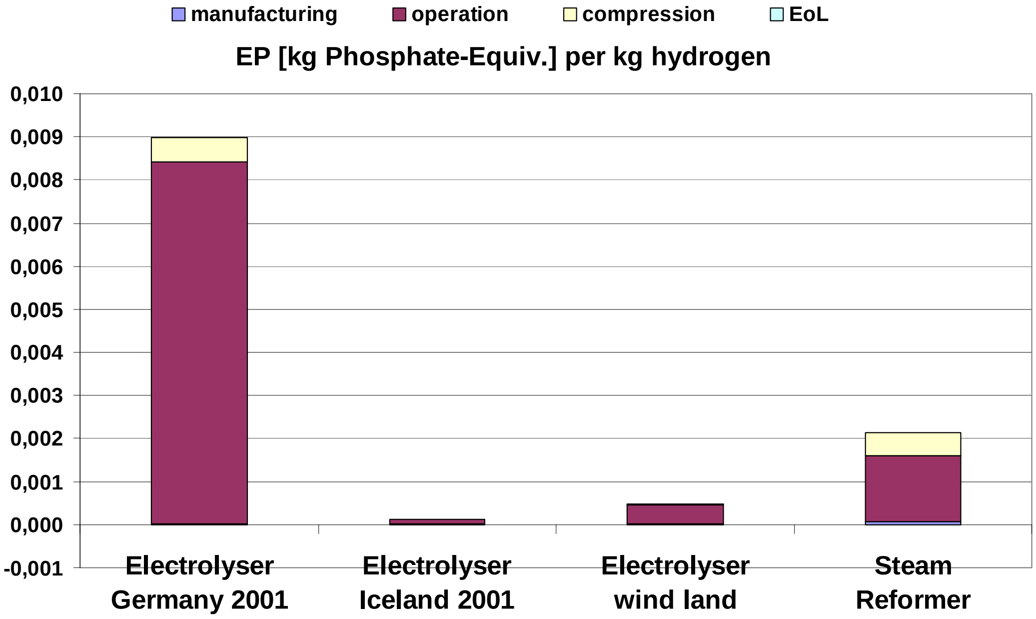


Figure 4-11: Hydrogen production – Eutrophication Potential (EP)

The main contribution to the eutrophication potential of all considered scenarios is related to NO_x emissions (between 55 % and 70 %). While for electrolyser the NO_x emission are at least 90% coming from energy production (scenario Germany 2001 nearly 100 %) in case of steam reformer approximately 35 % are direct emissions by the reforming process, 19 % are related to the German import mix of natural gas and 38 % are related to the consumed electricity for utilities and compression.

More than 90 % of the POCP (see Figure 4-12) is related to VOC (28 % ÷ 64 %), SO_2 (22 % ÷ 52 %) and NO_x (9 % ÷ 15 %) emissions. While for electrolyser German and Icelandic grid mix SO_2 emissions with approx. 52 % / 43 % are the main contributing emission in case of electrolyser wind land (approx. 54 %) and steam reformer (approx. 64 %) VOC emissions are the main contributor. Analysing the steam reformer further show, that approx.65 % of the POCP is related to the beneficiation and distribution of the natural gas and only approx. 5 % are related to direct process emissions by the process itself. The negative values for the End-of-Life (EoL) result from credits that are given for the recycled materials of the H_2 infrastructure components. Usually the recycling process leads to a certain degree of down cycling. Also the efforts in terms of energy consumption and processing for the recycling itself and material specific recovery rates are considered. Therefore the EoL values are lower than the manufacturing.

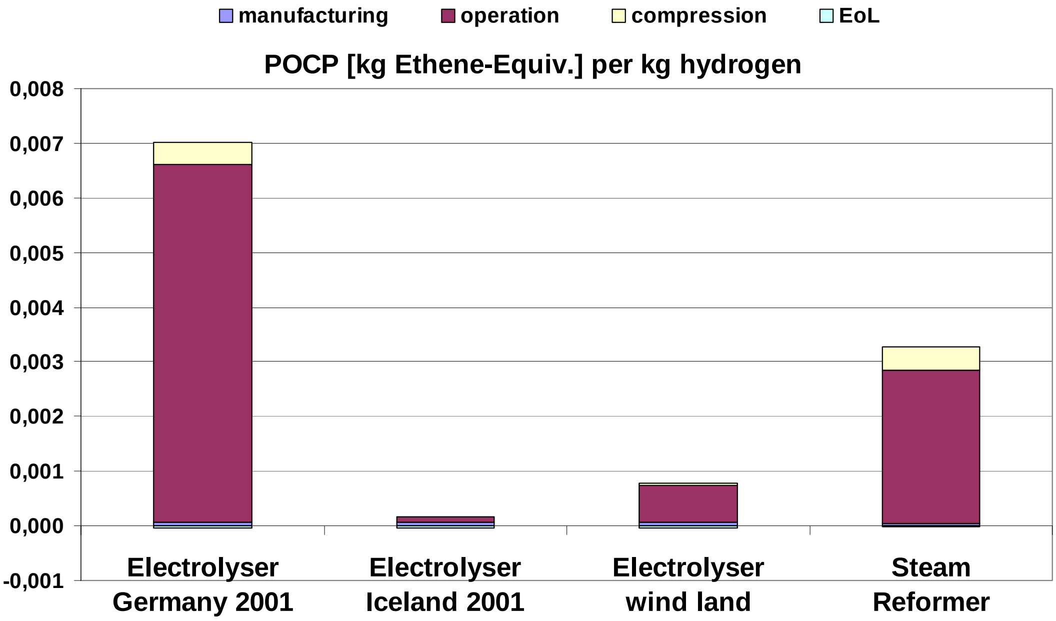


Figure 4-12: Hydrogen production – Photoch. Ozone Creation Potential (POCP)

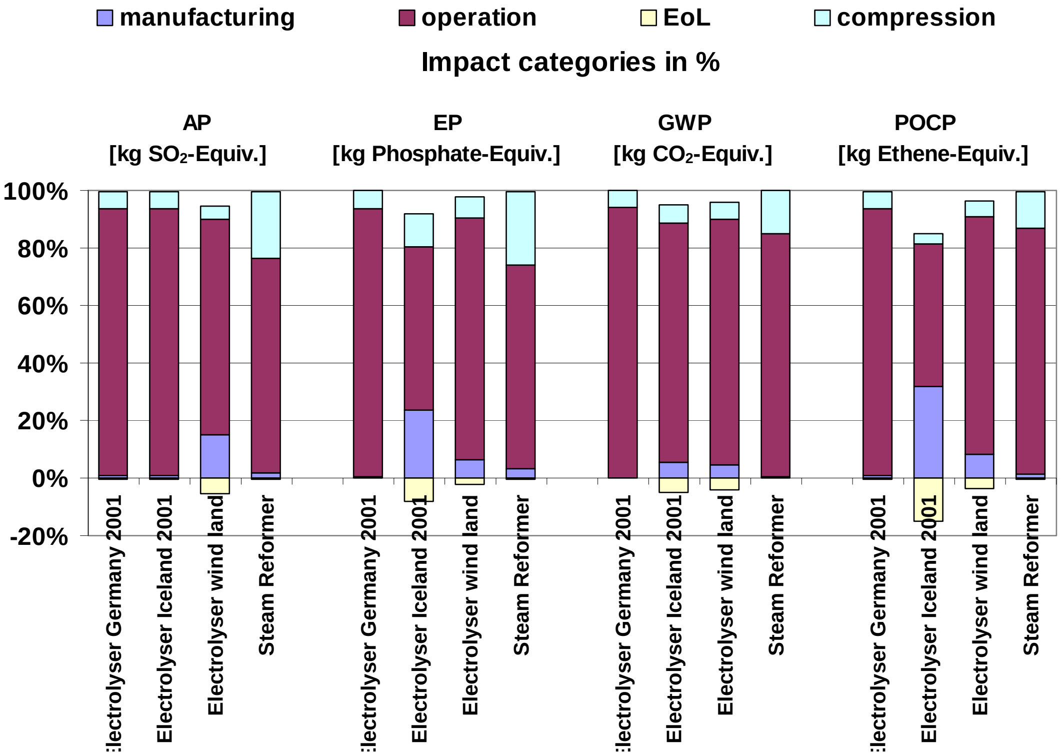


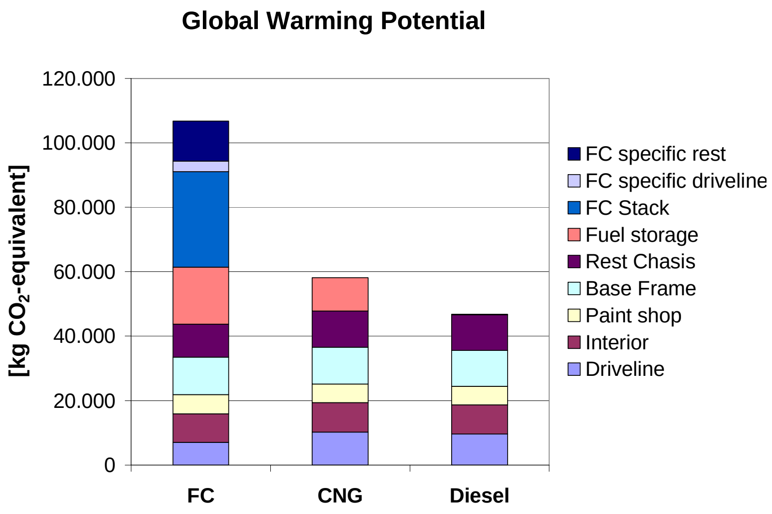
Figure 4-13: Hydrogen production – Impact categories

Analysing the relative contribution of the different life cycle stages, see Figure 4-13, show that the manufacturing phase becomes relevant when renewable energy sources are used. Also it can be seen that the compression of the hydrogen to 440 bar has an influence on the overall environmental footprint. The highest influence of the compression can be seen for the Steam Reformer and is mainly related to the energy consumption of the compressor.

The contribution to the impact categories from operation for electrolysis using wind energy is coming from building and maintaining the power plants while when using the Icelandic grid mix they are also related to direct emissions from geothermal power generation (CO_2, H_2S and methane) and also from aerobic and anaerobic digestion of biomass in the water reservoir, counted as CO_2 equivalents. For example approximately 90 % of the acidification potential of the operation phase and the compression is related to geothermal power and more than 95 % of this is related to direct H_2S emissions.

4.2.4 LCIA results of the bus manufacturing

The Global warming potential as shown in Figure 4-14 corresponds well with the overall primary energy demand (see Figure 3-49). The fuel cell bus has roughly twice as much GWP than the diesel bus. For the POCP the increase for the FC bus compared to the diesel bus is less due to the higher relative share of the paint shop caused by the VOC emissions from the application of solvent based paint system components which is the same for all three buses.



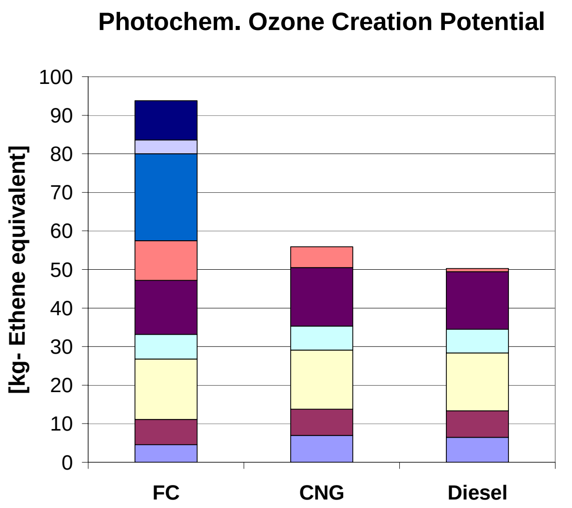


Figure 4-14: Global warming potential (GWP 100a)

Figure 4-15: Photochemical ozone creation potential

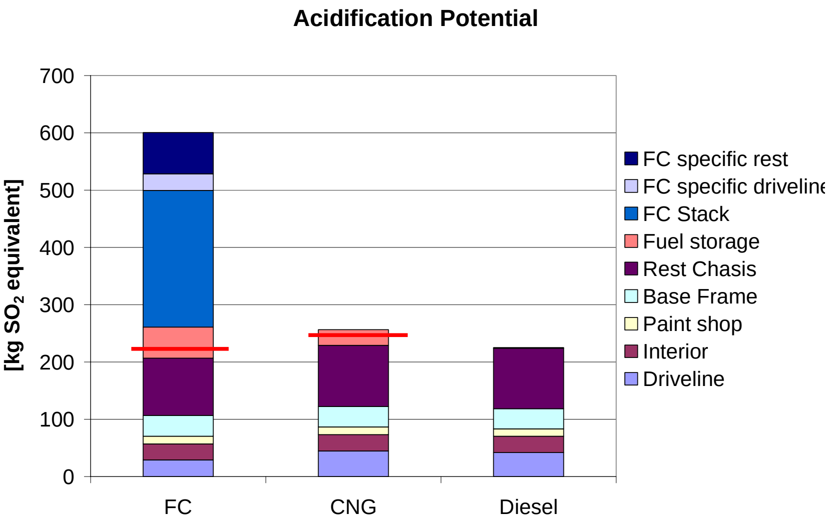


Figure 4-16 Acidification Potential bus manufacturing

Due to the high SO_2 and NO_X emissions from the electricity production needed during primary platinum manufacturing the FC stack contributes an even higher share to the Acidification potential (AP) leading to roughly 3 times higher values than the diesel bus.

4.2.5 LCIA results of the complete bus Life Cycle

Putting together the bus manufacturing, the fuel supply, the operation of the buses on a specific route and finally the End of Life the considered bus systems have the environmental impacts as shown in Figure 4-17and Figure 4-18 over their life cycle.

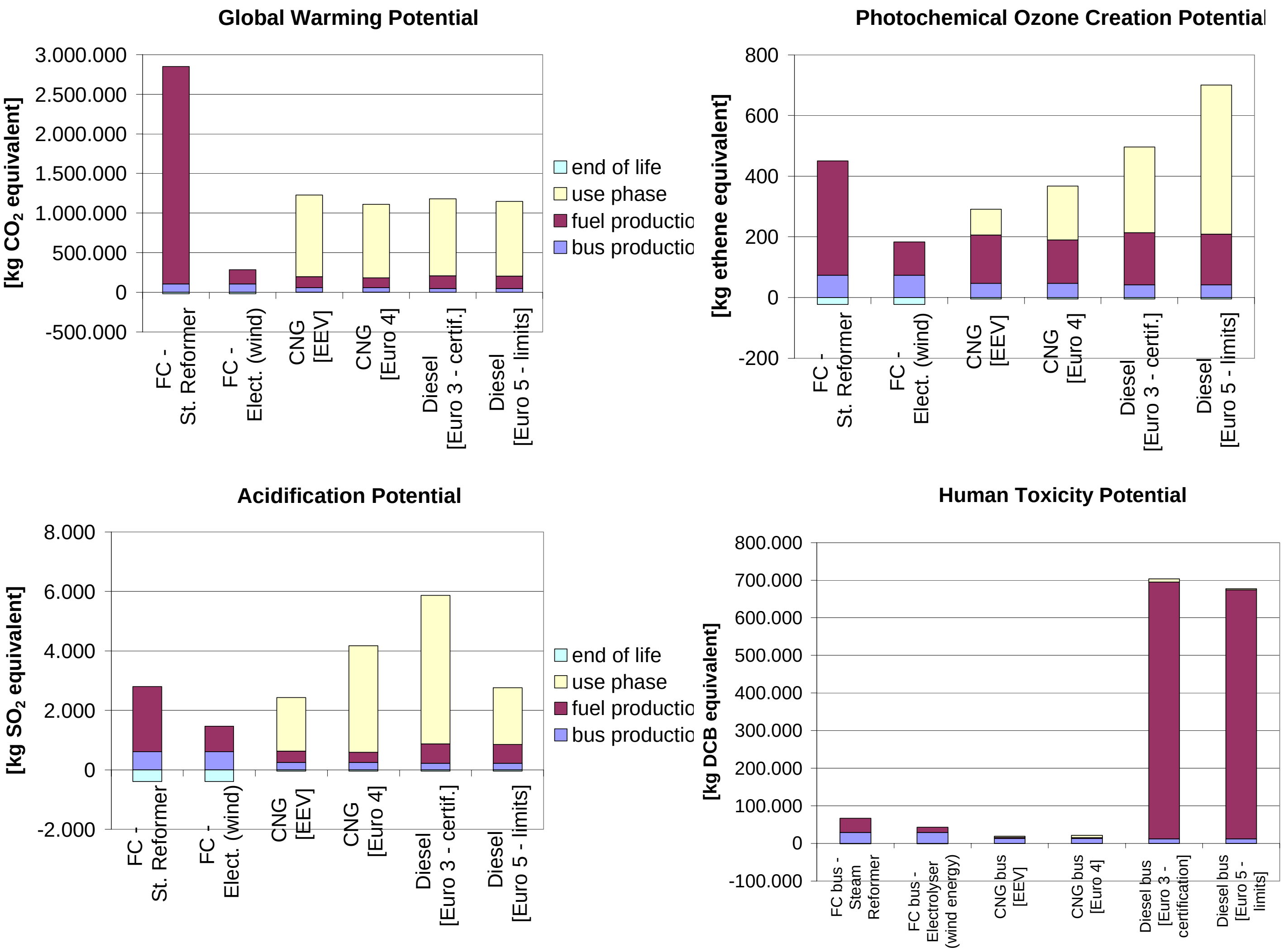


Figure 4-17: Selected environmental impact categories – Line 42

With it s current consumption data the FC system using hydrogen from natural gas steam reforming is not competitive with diesel and CNG buses. But using hydrogen produced from renewable sources (in this case from electrolysis using wind power) the FC system is the best choice in terms of mitigation of greenhouse gases. The CNG bus has a slightly higher or lower GWP than the diesel bus, depending on which Euro level and which cycle is considered. In terms of POCP better known as summer smog potential the FC system using H_2 from natural gas is comparable with the Diesel Euro 3 bus. The other conventional buses have a lower POCP with CNG buses having an advantage over diesel buses. The FC bus using "renewable" hydrogen has again the lowest environmental impact in this category. This also applies to the next 2 categories Acidification (AP) and Human toxicity potential (HTP). The FC bus using hydrogen from natural gas is comparable to the AP of the CNG EEV bus and Diesel Euro 5. The decline of AP form CNG and diesel from one Euro Level to the next relates mainly to the reduced NO_x emissions during operation. In terms of HTP the CNG buses followed by the FC buses are the best options both showing an improvement by several orders of magnitude compared to the fine particles emitting diesel buses.

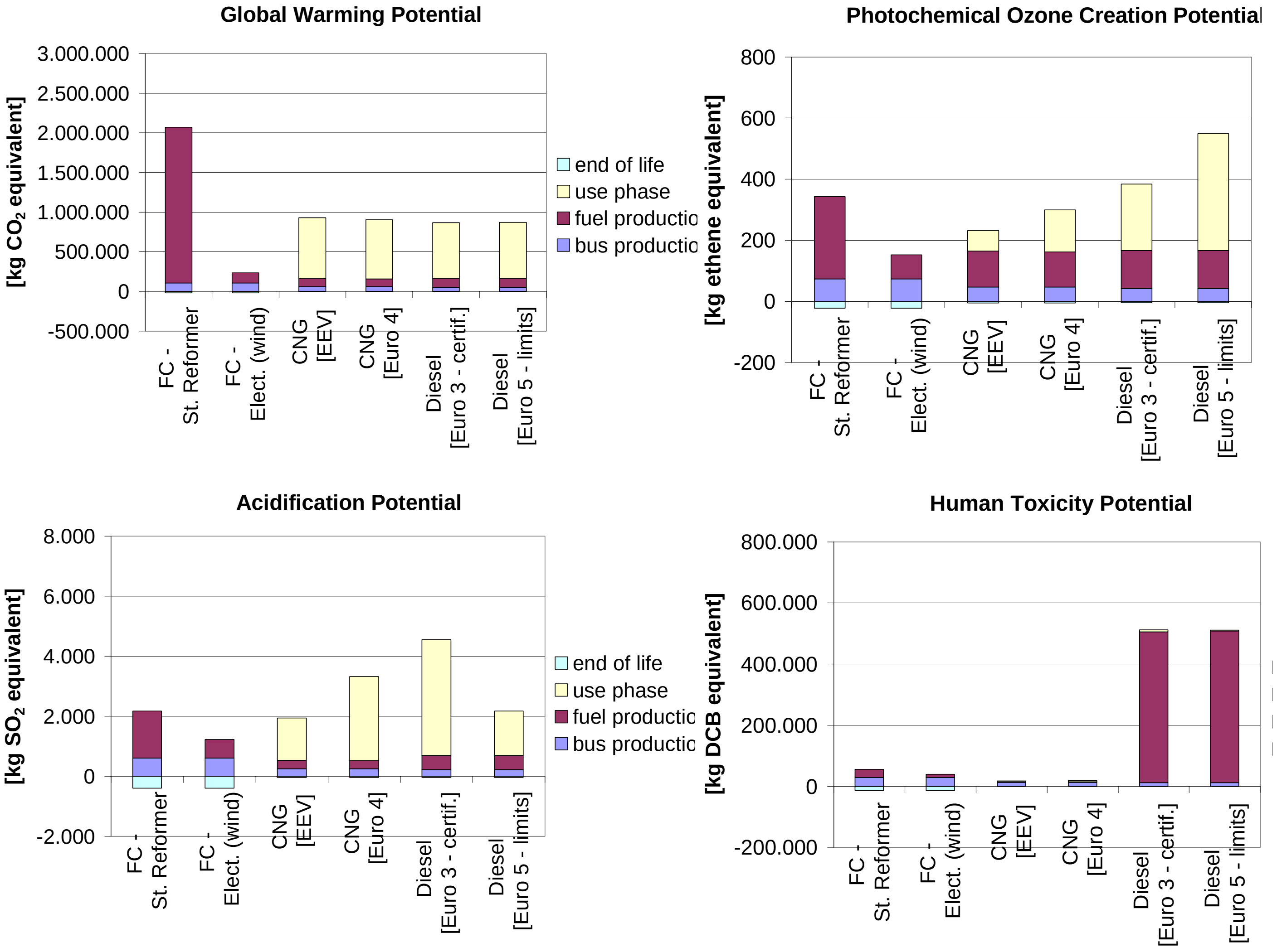


Figure 4-18: Selected environmental impact categories – Esslingen Cycle

The eutrophication potential for Linie 42 and the Esslingen cycle are listed in Figure 5-6, Figure 5-7 in Appendix C.

4.2.6 Exemplary normalisation of hydrogen production

As already mentioned in chapter 4.1.4 there are no normalisation factors for Iceland available Despite the fact that a normalisation to the averaged European conditions does not really represent the Icelandic boundaries a normalisation for the hydrogen production in Iceland was carried out to see what kind of results a normalisation would provide and if the results were interpretable.

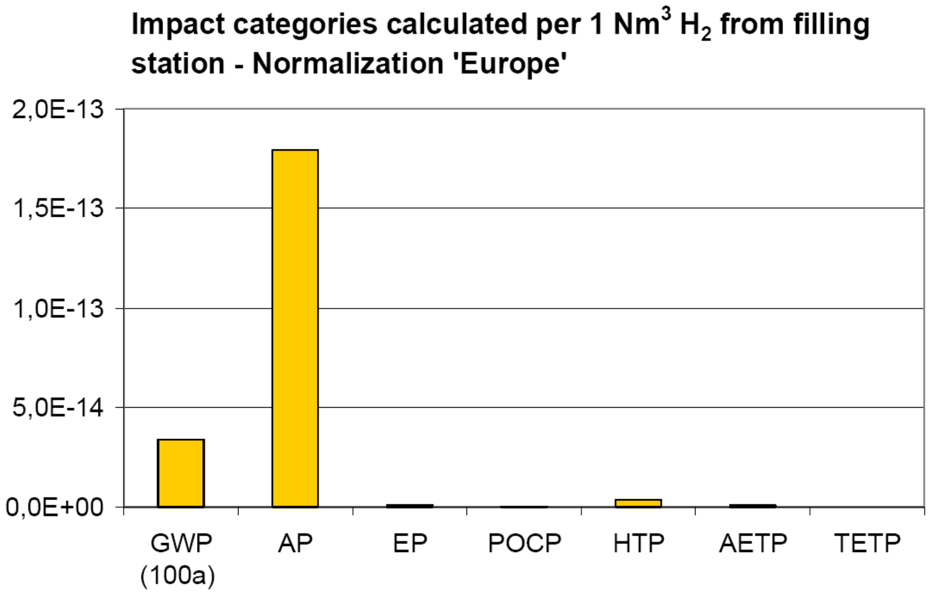


Figure 4-19: Impact categories for hydrogen station, normalisation 'Europe'

Looking at Figure 4-1 the acidification potential (AP) and the GWP appear as significant hot spots which can be explained as follows.

The AP is caused by the electricity demand for the production of H_2 and therefore by the power generation in Icelandic geothermal plants.

Two main facts should be remarked regarding the high acidification potential. The first point is that it is assumed for the calculation of the AP that H_2S is converted to SO_2 that causes for example acid rain. As mentioned in [30], that the conversion from H_2S to SO_2 is minor, or at least very slow, at atmospheric conditions in Iceland [28]. In addition, the H_2S gas can be converted into sulphur that may then react with the soil to form sulphates like gypsum, which is not harmful for the environment.

The second point is that H_2S is emitted from most of the high-temperature fields prior to their development. Fumaroles or hot springs are possible sources. The H_2S emission is therefore related to the Icelandic country due to its geological structure. The additional emission from the power plants should be considered on this background.

Similar considerations are valid regarding CO_2 that contributes to the GWP. It is also an emission that occurs naturally in Iceland. But it should be mentioned that in recent years 70 % of the total CO_2 emission in Iceland was caused by the use of fossil fuels (industry, transport sector, fishing fleet). Just around 5 % were emitted from high temperature geothermal plants.

The interpretation of the results would be more difficult due to the complexity of the whole system. Such an analysis would be very resource intensive and would go beyond the scope of this study. Furthermore the possibility of having different overlying effects in the various subsystems would lead to results which would be connected with a high level of uncertainty. Considering theses aspects a normalisation for the complete FC bus system was not carried out in this project.

5 Life Cycle Interpretation, summary and findings

The results and findings are representative for prototypes (FC-bus and hydrogen infrastructure). They serve as a baseline to determine improvement potentials and to measure future improvements against.

5.1 Summary

The results of the LCA study can be summarised as follows:

Complete life cycle:

- A modular Life Cycle Inventory (LCI) model for the manufacturing, operation (incl. fuel supply) and EoL of different bus technologies was developed. It allows to quantify the environmental life cycle profile of Fuel cell, Diesel and CNG buses. The model enables the user to determine the module specific contribution to the environmental footprint.
- The LCA indicates a fundamental shift of burdens for the FC bus system: the direct emissions from bus operation are completely shifted to the fuel supply.
- The environmental profile of FC bus system is highly dependant on the chosen H_2 supply route and efficiency of FC system.
- The H_2 production via steam reformer using natural gas needs to be improved to be competitive with fossil fuels in terms of CO_2.
- The FC-bus system show its advantages compared to conventional bus systems in terms of local environmental effects caused by direct emissions from use phase. The FC-technology shows the potential to improve air quality in urban areas with high traffic density tremendously.
- When using renewable resources for hydrogen production, the production of the infrastructure and the FC-bus determines the environmental footprint of the overall system. E.g. the emissions from manufacturing of hydrogen production facilities have a relevant share for routes using renewable energy sources, however on a significantly lower absolute level.
- The study combines the comparison of on-site hydrogen production routes based on different energy sources with conventional fuel production (diesel and CNG) in two European countries.

- Using the developed LCI model it is possible to evaluate the impact of a hydrogen based road transportation sector on Iceland. A scenario using first rough estimations was developed. (see Appendix F). A more detailed and up-to-date version of this scenario was developed in Deliverable 14.

Bus manufacturing (common for Diesel, CNG and FC):

- A modular Life Cycle Inventory (LCI) model was developed for the manufacturing of different bus technologies for the first time. It is structured according to the main modules, e.g. body in white, interior, drive train, FC stack, fuel storage.
- The manufacturing of the components was modelled using average numbers on production processes representing the state of the art.
- The paint shop dominates the VOC-emissions due to the use of solvent based paint.

FC-bus specific manufacturing:

- In terms of the primary energy demand, CO_2 and SO_2 emissions the bus chassis has a share of 40 % and the FC system a share of 60 %.
- FC System: The primary energy demand and CO_2 emissions are dominated by H_2 storage with a share of 36 % (mainly related to carbon fibre production) and the FC stacks, having a share of 37 %. The manufacturing process is only relevant for the primary energy demand since the electricity used during manufacturing of the FC drive train is based on renewable energy (96 % hydro power for British Columbia, Canada).
- The FC drive train shows high electricity consumption for production and testing of fuel cell stack.
- The platinum used in the FC stack has a high impact on SO_2 emissions due to its energy intensive beneficiation process in South Africa and the South African grid mix.
- Existing data gaps have been closed by expert judgement in collaboration with the Engineering department from the bus and the FC drive train manufacturer.

For the fuel supply

- In terms of primary energy demand from non renewable sources and emissions hydrogen produced from renewable sources displays its advantage.
- The electricity from the German grid consumed by the steam reformer and the compressors account for approx. 40 % of the CO_2 emissions.

- The influence of country specific energy supply chains is of critical importance for all investigated fuels.

Operation:

- The drive train of the fuel cell buses used in ECTOS and CUTE was optimised focusing on reliability. With a reliability > 90 % the FC Citaro buses exceeded any expectation by far. However the optimisation for reliability resulted in reduced fuel efficiency. Compared to the conventional buses the FC bus trailed the Diesel bus but showed comparable fuel economy to the CNG bus. The NEBUS, a FC bus solely designed to demonstrate best available technology in terms of efficiency shows by far the best fuel economy. It can serve as a benchmark with regard to fuel consumption for the next generation of FC buses.

End of Life / Recycling

- The LCA can also be used to determine optimisation potentials within the End of Life and recycling phase. E.g. the reduction potential of environmental impacts by recycling the used platinum can be quantified.

5.2 Significant parameters

As mentioned in chapter 5.1 the main significant parameters for the environmental performance of the hydrogen / FC-bus system are the chosen supply route and the fuel consumption of the buses. Emissions of the operation phase of the buses result from the hydrogen production. Hydrogen production based on mainly renewable resources leads to relatively low emissions but in the case of Iceland requires a higher primary energy demand.

For the diesel and CNG bus system bus operation dominates most of the emissions. Fuel production is relevant for POCP (VOC-emissions).

In Iceland manufacturing phase for bus system and hydrogen station is not negligible, since the use of renewable energy sources leads to an increased relevancy of the manufacturing of the power and hydrogen production plant.

5.3 Evaluation

The evaluation of this LCA study addresses the completeness of the data and the sensitivity of results. Based on the developed life cycle model and its results it is also possible to extrapolate the implications of introducing hydrogen for the whole transportation sector in Iceland. Finally it also includes a data quality assessment.

5.3.1 Completeness

In the study all relevant parts of the life cycle of bus system are considered. According to cut-off-criteria negligible parts like infrastructure for resources beneficiation are not considered, as they are not relevant for the overall results of the study. Completeness of data is very high, especially the bus manufacturing and hydrogen station including all components and upstream processes are considered in detail with high quality data directly provided by industry (participating companies).

5.3.2 Sensitivity analysis

To assure quality of results sensitivity analyses were made during the modelling process and parts with significant impact on the results were analysed in detail. Within the study several iteration steps were made to achieve a quality representing state of the art. The focus of areas for sensitivity analysis has been areas where assumptions by the project team have been necessary due to lack of data. In case of assumptions with significant relevance to the results, iterative data quality improvement in consultation with involved partners was done. Made assumptions are stated in chapter 3.2 within the data collection and calculation procedures.

5.4 Data Quality Assessment

5.4.1 Fuel supply

ELECTROLYSER AND ELECTRICITY GENERATION

Data quality for electrolyser life cycle is very good; direct industry data from electrolyser producer could be used. Material and energy inputs including upstream processes are based on industry data, statistical data and various literature sources. Electricity generation in Iceland is modelled on basis of statistical grid mix as well as detailed information from power plant operating company.

STEAM REFORMER AND NATURAL GAS SUPPLY

Data quality for steam reformer life cycle is very good, direct industry data from producer could be used. Material and energy inputs including upstream processes are based on industry data, statistical data and various literature sources. Natural gas supply is modelled on basis of country specific statistical import mix and detailed information on gas supply including logistics and gas gathering in main natural gas exporting countries.

DIESEL PRODUCTION AND CRUDE OIL SUPPLY

Data quality for diesel supply chain including refinery and crude oil supply is very good. The refinery model based on literature data as well as on direct information of refineries. Crude oil supply is modelled on basis of country specific statistical import mix and detailed information on upstream processes including logistics and oil gathering in main crude oil exporting countries. The refinery model was created using various literature and experts and has been validated by refineries.

5.4.2 Bus system

MANUFACTURING:

Data quality was good due to the usage of detailed bill of material information allowing detailed modelling of weights and material composition on single part level. The information for processing of parts and materials was available for specific parts and assembly groups.

OPERATION:

Data quality for consumption data is very good, based on several specific measurement trials and for FC buses detailed monitoring of consumption data on a daily basis has also been done. For emission data the data quality is satisfactory considering the available literature data. Taking into account that measurement data for two different cycles will also become available in the near future for the CUTE project the data quality can be considered as very good.

END OF LIFE:

Data quality can be considered as satisfactory since no detailed investigations concerning the recycling of a public transportation bus or coach were available. For the dismantling processes data from passenger car recycling were used. The quality of material composition data and data on material recycling processes can be considered as good. The model represents state-of-the-art of LCA studies in automotive industry.

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APPENDIX

Appendix A Electricity production

HYDRO-POWER

The electrical plant efficiency takes the following aspects into account: efficiency of turbines, generators and the losses when the water flow passes components of the system e.g. bendings in tubes (reference is the potential energy of the water at the intake building):

The main power plant specifications are listed in the table below.

Blanda power station – specifications-[30]		
Catchment area	1520	km^2
Average discharge	39	m^3/s
Gross head	287	m
Main reservoir area at 478.0 m a.s.	56	km^2
Usable storage capacity	400	Gl
Intake reservoir	5	km^2
Usable storage capacity	20	Gl
Installed capacity (3 Francis turbines, 50 MW each)	150	MW
Annual energy production capacity	720	GWh/a
Life span	60	a
Efficiency	87	%
Sulfur hexafluoride (SF_6) losses	100	g/a
Greenhouse gas (GHG) emissions (without SF_6)	1	g/kWh

The hydroelectric power plant is dismantled after its decommissioning. The main processes and the deposition of the main demolition wastes is shown in the table below. Credits are given for recovered materials, mainly recycled metals.

Assumptions concerning waste processing / recycling	
Steel in foundations of power house and dams	No recovery
Steel, copper, aluminum	Recovery and recycling
Batteries and used oil	Waste processing
Demolition wastes: concrete, cement, tarmac, bitumen	Deposition at landfill site
Plastics	Deposition at landfill site
Wood, pressboard, millboard	Deposition at landfill site
Manganese, zinc from dry batteries	Deposition at landfill site

GEOTHERMAL POWER

The energy source for geothermal power plants is the enthalpy of steam and hot water from the geothermal underground systems at high temperature fields. The steam with its potential energy streams through the turbine blades and is transformed into kinetic energy that is then converted into mechanical energy by the rotation of the turbine axle.

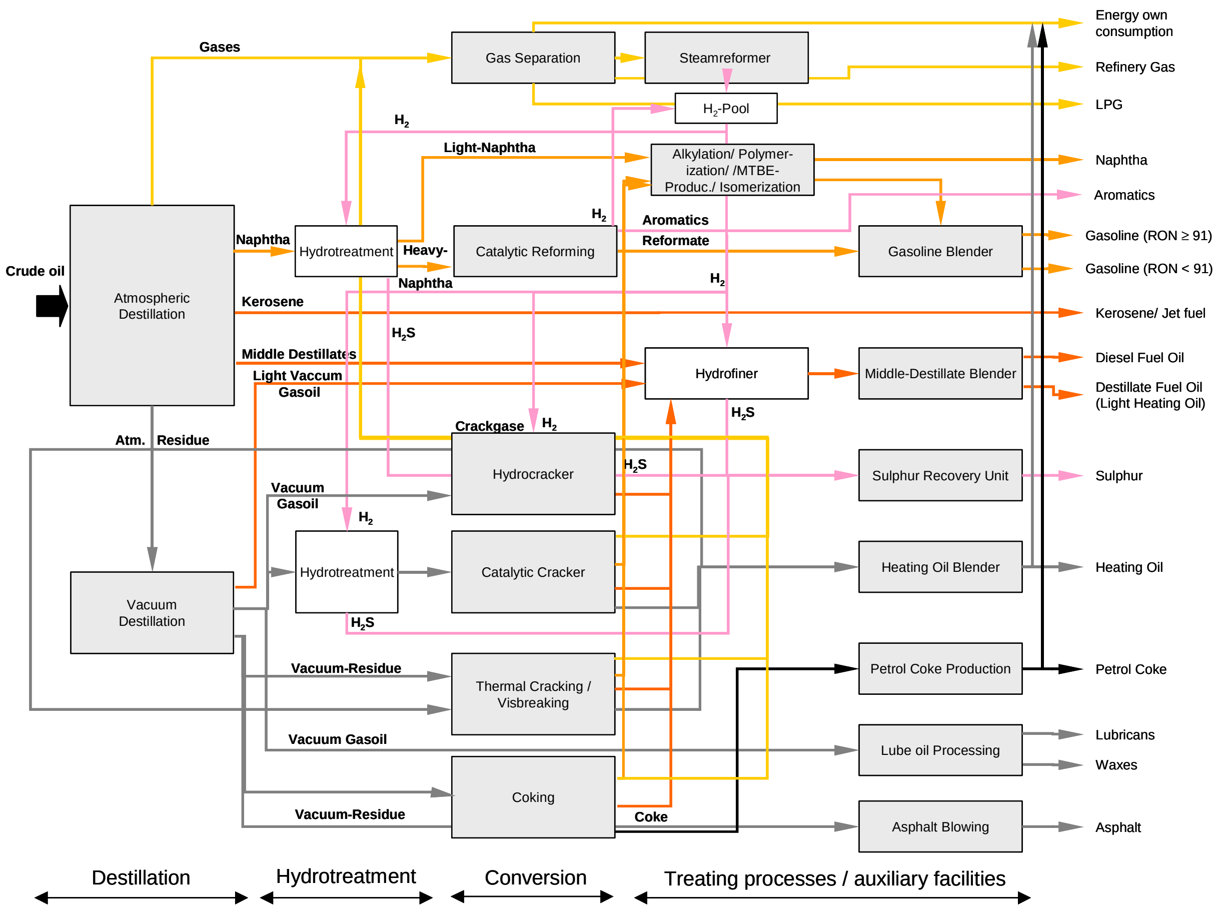
Assumptions and operation parameters geothermal power plant [30]		
Lifespan	30	a
Efficiency of average geothermal power plant (without co-generation)	17	%
Installed capacity	30	MW
Annual power generation capacity	250	GWh
Power plant availability	95	%
Amount of geothermal dry steam needed for 30 MW_{el}	50	kg/s
Average enthalpy of dry geothermal steam	2,6	MJ/kg
Sulfur hexafluoride (SF_6) leakage per year	100	g/a

To keep the power plants capacity stable, it is necessary to connect new production wells. The assumption for this study is that one new production well is connected every four years. A summary of the amount of wells is given in the table below.

Type of well [30]	*Amount*
Production wells connected when operation starts	5
Additional production wells to be drilled during operation (~one every 4 years)	7
Re-injection wells connected when operation starts	2
Additional re-injection wells to be drilled (half as much as production wells)	3

Appendix B Diesel fuel production in Germany - Refinery

FLOW CHART: REFINERY



REFINERY PRODUCTS

Output	***2003 [Wt%]***	***Average caloric value [MJ/kg]***
Refinery gas	0,42	50,0
Hydrogen	0,00	120,0
Propane	0,79	46,4
Propylene	0,69	45,8
Butane	0,92	45,7
Butylene	0,73	45,3
Naphtha	7,43	44,5
Aromatics	0,20	44,5
Gasoline (RON ≥ 95)	15,50	44,5
Gasoline (RON 91)	6,90	44,5
Kerosene (including, Aviation Gasoline, Jet Fuel)	3,62	42,7
Diesel Oil	25,00	42,7
Distillate Fuel Oil (Light Heating Oil)	16,20	42,7
Heating Oil (Residual Oil)	9,69	41,0
Lubricants	0,99	38,0
Waxes / Paraffins	0,20	38,0
Asphalt	2,97	39,0
Petrol Coke	0,98	29,0
Sulphur	0,53	9,25
Energy own consumption (including refinery losses)	6,28	
Sum	**100,00**	

Table 5-1: Refinery product slate

In addition to the “Energy own consumption” (confer to Table 5-1) the refinery requires the following external energy:

- Electricity: 0,021 kWh per kg crude oil input
- Natural gas: 0,35 MJ per kg crude oil input

Appendix C Bus system

<table>
<tr><th></th><th>Diesel</th><th>CNG</th><th>Fuel Cell</th></tr>
<tr><td>Dimensions</td><td colspan="3"></td></tr>
<tr><td>Length</td><td colspan="3">11.950 mm</td></tr>
<tr><td>Width</td><td colspan="3">2.550 mm</td></tr>
<tr><td>Height</td><td>3.009 mm</td><td>ca. 3.500 mm</td><td>3.530 mm</td></tr>
<tr><td>Wheel base</td><td colspan="3">scope of delivery</td></tr>
<tr><td>Overhang front/rear</td><td colspan="3">2.705/3.400 mm</td></tr>
<tr><td>Embankment angle</td><td colspan="3">7°/7°</td></tr>
<tr><td>Standing height</td><td colspan="3">2.313 mm</td></tr>
<tr><td>Number of doors</td><td colspan="3">3</td></tr>
<tr><td>Propulsion</td><td colspan="3"></td></tr>
<tr><td>Engine</td><td>OM 906 LA (Euro 3)</td><td>OM 447 hLAG IV/21</td><td>Reuland electric engine</td></tr>
<tr><td>Number of cylinders</td><td>6 (in line) standing</td><td>12 (in line)</td><td>-</td></tr>
<tr><td>Power outpu</td><td>205 kW</td><td>185 kW</td><td>220 kW</td></tr>
<tr><td>Torque</td><td>1.100 Nm</td><td>900 Nm</td><td>1050 Nm</td></tr>
<tr><td>Transmission</td><td>Voith 4 gear</td><td>ZF HP 502</td><td>ZF 6HP 502</td></tr>
<tr><td>Chasis</td><td colspan="3"></td></tr>
<tr><td>Brakes</td><td colspan="3">4 disc brakes</td></tr>
<tr><td>Front axle</td><td colspan="3">MB VO 4/39 CL-7,5</td></tr>
<tr><td>Rear axle</td><td colspan="3">ZF Portal axle AV 132/80° (LA)</td></tr>
<tr><td>Track f-axle</td><td colspan="3">2.101 mm</td></tr>
<tr><td>Track r-axle</td><td colspan="3">1.834 mm</td></tr>
<tr><td>Turning circle</td><td colspan="3">D: 21,3 m</td></tr>
<tr><td>Tire size</td><td>275/70 R 22,5x7,5</td><td>275/70 R 22,5x7,6</td><td>295/60 R 22,5x7,7</td></tr>
</table>

Table 5-2: Main vehicle characteristics

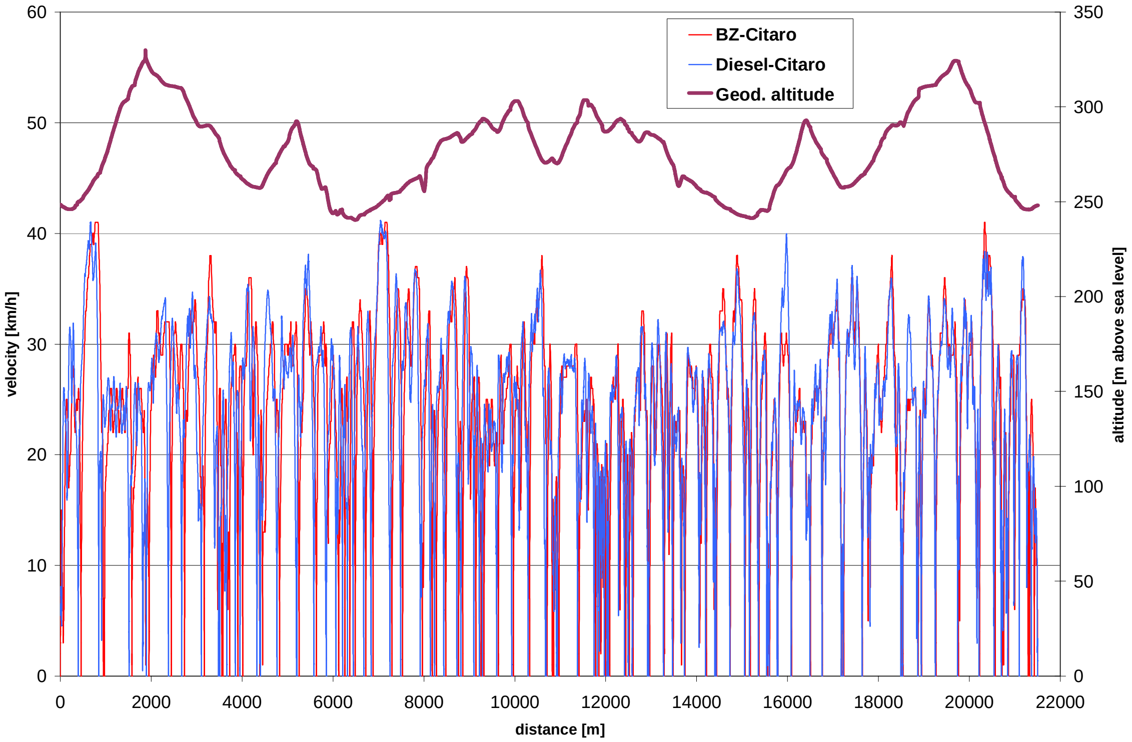


Figure 5-1: Speed and altitude profile of Line 42

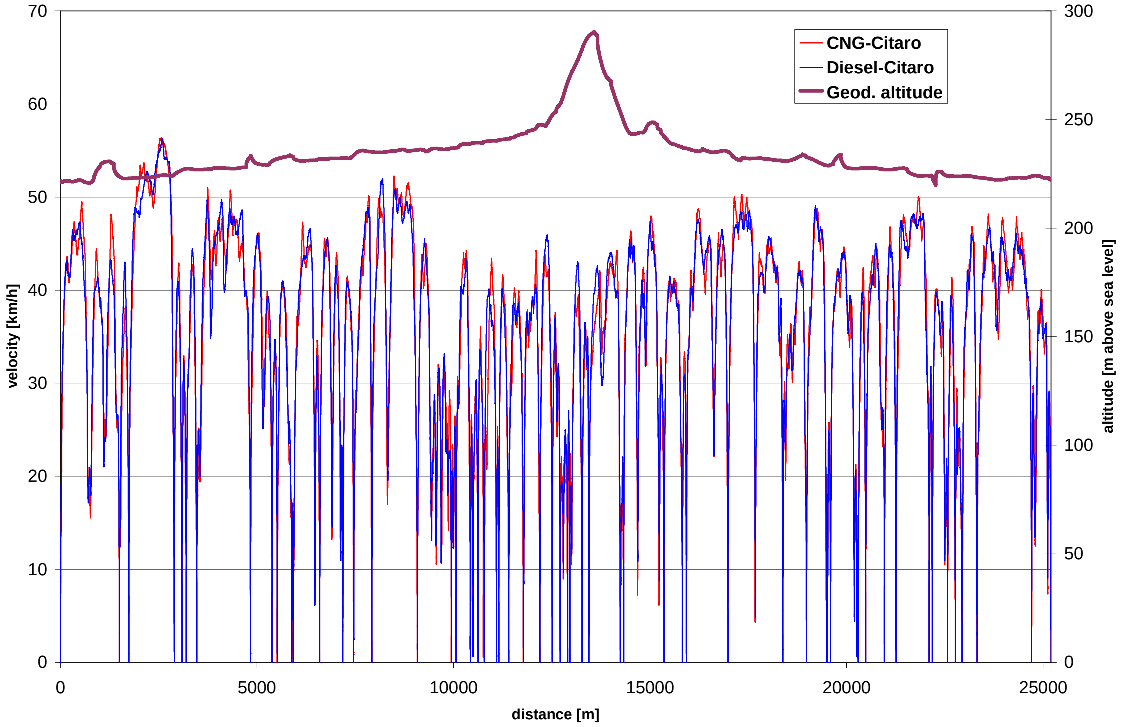


Figure 5-2: Speed and altitude profile of Esslingen cycle

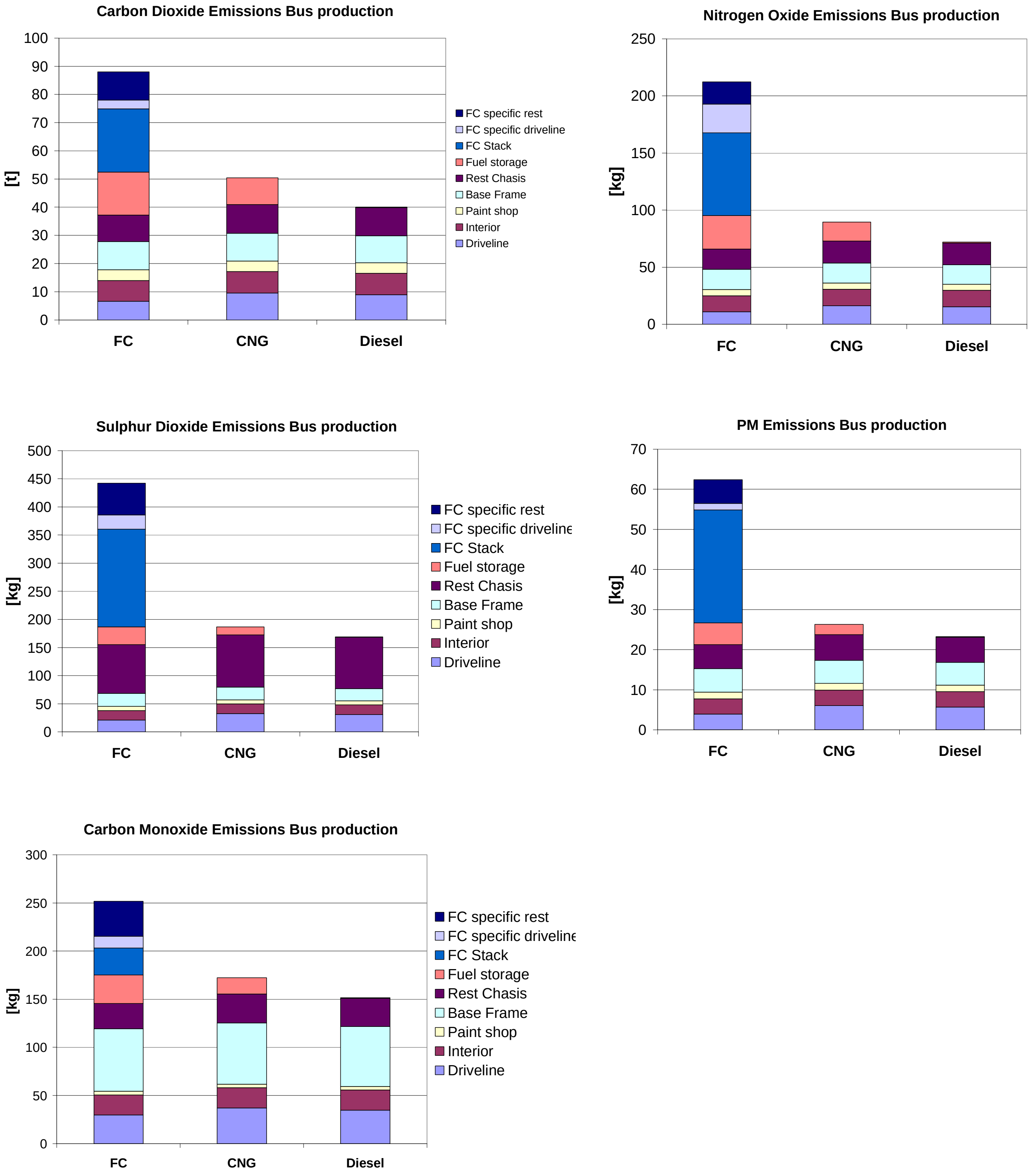


Figure 5-3: Bus manufacturing – emissions to air

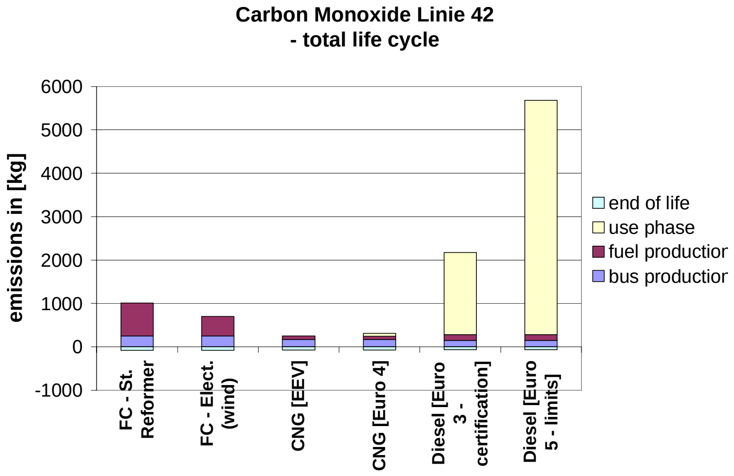


Figure 5-4: Life Cycle inventory – emissions to air Line 42

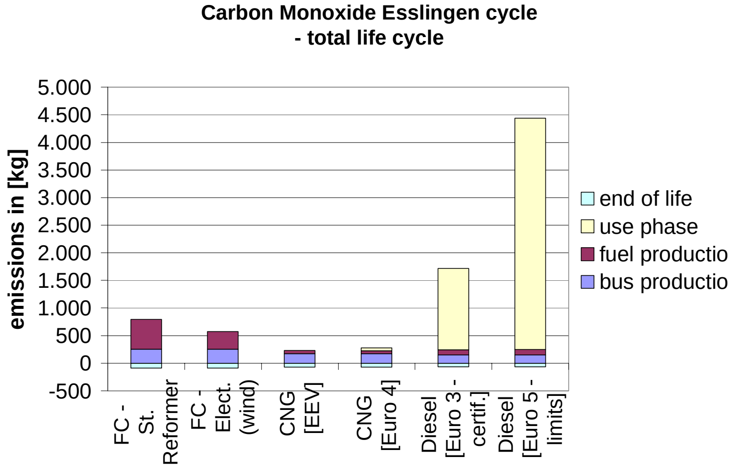


Figure 5-5: Life Cycle inventory – emissions to air Esslingen cycle

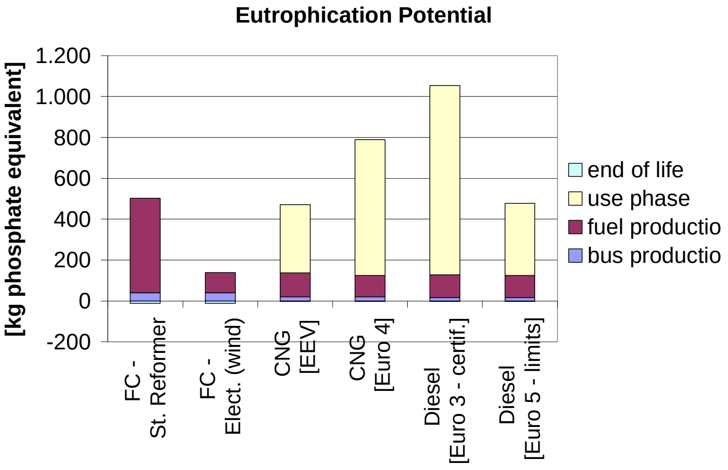


Figure 5-6: Life Cycle Impact Assessment – selected categories Line 42

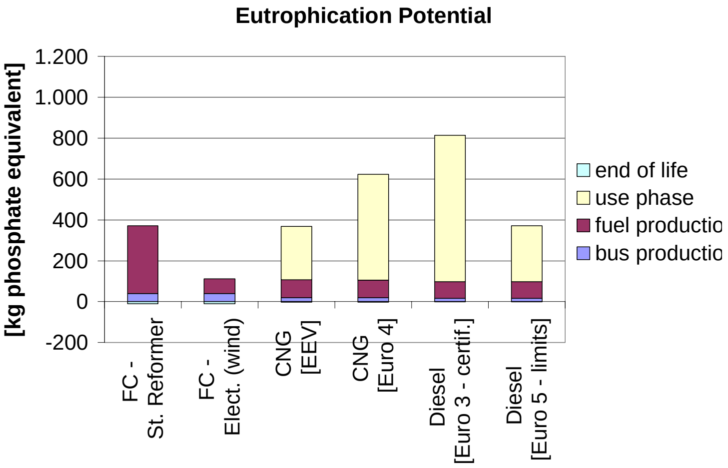


Figure 5-7: Life Cycle Impact Assessment – selected categories Esslingen cycle

Appendix D Diesel fuel supply in Iceland – Diesel fuel production in Norway – Comparison with Germany

Iceland has no crude oil refinery. Thus the total amount of diesel fuel is imported. In 2001, the main origin countries were Norway and FSU. The following discussion will focus on the of diesel fuel in Norway due to their relevance in terms of the total import share. Furthermore, the Norway diesel fuel production is compared with German one.

For more information on the operation principle of a refinery, system boundaries and functional unit, etc. see chapter 3.2.6.

Norway operates 2 petroleum refineries with a capacity of 15,5 10^6 tons per year [31]. The average utilisation of the atmospheric distillation is assumed to be 95,0 % in 2003.

Relevant properties of the refinery input and output (2003), [13]

Crude oil:

	Germany	***Norway***
Sulphur content [wt%]	1,0	0,33
Density [kg/dm³]	0,842	0,823

Products:

- Sulphur content:

	Germany	***Norway***
Diesel fuel	10 ppm (0,001 wt%)	30 ppm (0,003 wt%)
Density [kg/l]	0,835	0,835

Refinery products (2003)

Output	***Germany [%]***	***Norway [%]***
Refinery gas	0,42	0,52
Hydrogen	0,00	0,10
Propane	0,79	0,98
Propylene	0,69	0,25
Butane	0,92	0,98
Butylene	0,73	0,17
Naphtha	7,43	8,48
Aromatics	0,20	0,00
Gasoline (RON ≥ 95)	15,50	22,47

Output	***Germany [%]***	***Norway [%]***
Gasoline (RON 91)	6,90	1,18
Kerosene (including, Aviation Gasoline, Jet Fuel)	3,62	3,08
Diesel Oil	25,00	25,84
Distillate Fuel Oil (Light Heating Oil)	16,20	18,48
Heating Oil (Residual Oil)	9,69	11,28
Lubricants	0,99	0,00
Waxes / Paraffins	0,20	0,00
Asphalt	2,97	0,00
Petrol Coke	0,98	1,49
Sulphur	0,53	0,19
Energy own consumption (including refinery losses)	6,28	4,51
Sum	**100,00**	**100,00**

Table 5-3: Refinery product slate

A more detailed description of the energy own consumption (including refinery losses) is provided below:

Energy own consumption	*Germany* *[%]*	*Norway* *[%]*
Refinery gas (incl. LPG)	3,64	3,63
Heating oil (residual oil)	1,47	0,00
Petroleum coke	0,56	0,74
Refinery losses	0,61	0,14
Sum	**6,28**	**4,51**

Table 5-4: Energy own consumption (including refinery losses)

Energy und material balance of the refinery (2003)

(All data per 1 kg crude oil input)	*Germany*	*Norway*
Fuel demand [MJ]	1,93	1,47
Steam demand [kg]	0,18	0,15
Electricity demand [kWh]	0,05	0,04
Water use (estimated) [l]	0,2	0,2
Methanol consumption [kg]*	0,0003	-
Hydrogen consumption [kg]	0,0042	0,0016

* Methanol is used for the MTBE (Methyl-Tertiary Butyl Ester) production.

LCI results of the two refinery models (Germany, Norway)

In the following two tables the most relevant LCI results are demonstrated.

Primary energy demand, carbon dioxide, nitrogen oxides and dust emissions:

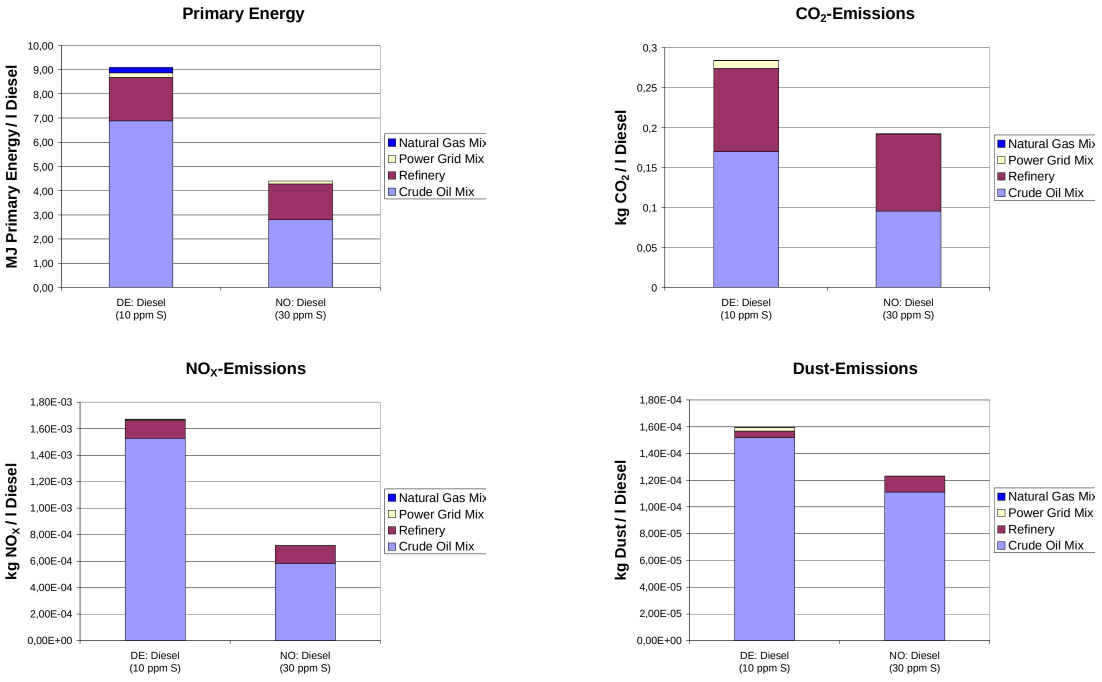


Table 5-5: Comparison of CO_2, NO_X, CH_4 and NMVOC emissions of the diesel fuel production

Table 5-5 and Table 5-6 show that the natural gas and electricity production have only a small influence (< 3,5 %) on the LCI results. Therefore, they are neglected in the following description (with the exception of CO_2 emissions).

The primary energy demand and the CO_2 emissions for the diesel fuel production are dominated (> 50 %) by the crude oil production followed by the refineries with curtly 45 %. The share of the CO_2 emissions caused by the power generation is only in Germany nameable, as Norway uses about 99 % hydro power for the generation of electricity.

The crude oil production is dominant for NO_X and dust emissions as well (> 80 % respectively > 85 %). Such as the primary energy demand and the CO_2 emissions, the total emissions are the lower in Norway compared with Germany. Reasons for the differences are different origins of crude oil. Especially the Scandinavian countries use better technologies for the production which causes lower emissions compared to countries e.g. in the Middle East. Norway converts only north sea crude oil (indigenous produced) and Germany only 36 % north sea crude oils in their refineries.

Sulphur dioxide, carbon monoxide, methane, and NMVOC emissions:

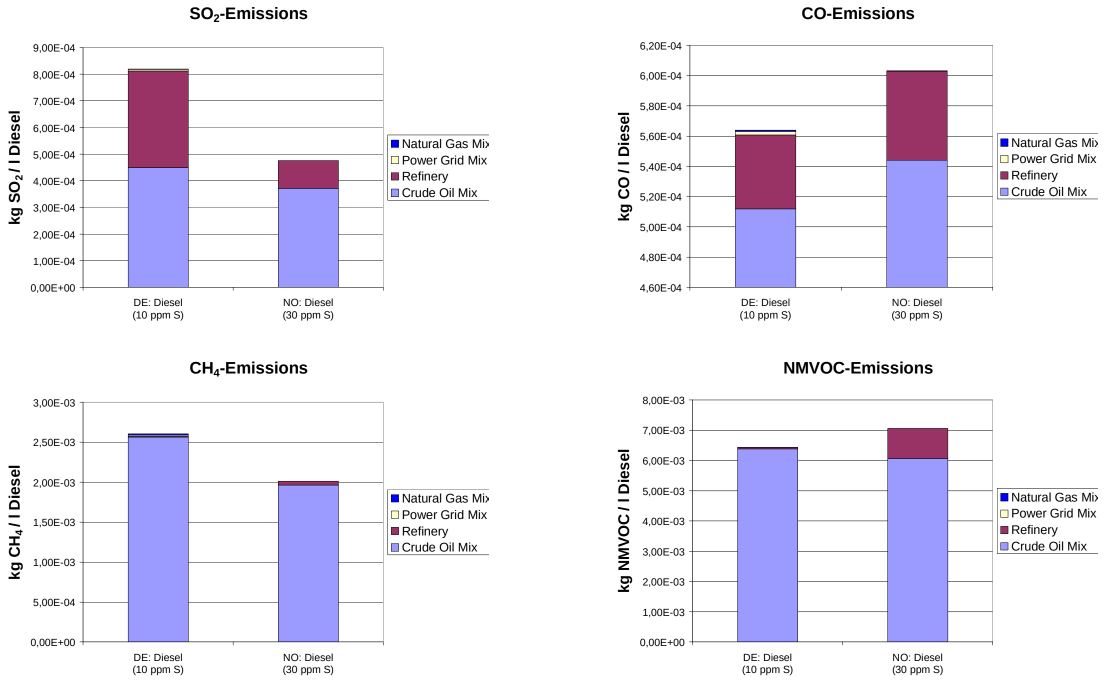


Table 5-6: Comparison of SO_2, CO and dust emissions of the diesel fuel production

The SO_2 emissions in German refineries are higher than the one in Norwegian refineries due to different sulphur contents in the crude oil and different flue gas cleaning efficiencies. Approximately 75 % of the CO, methane and NMVOC emissions come from the crude oil production.

Appendix E Comparison of grid mix (Iceland, Germany, UCTE)

To show the different environmental profiles of European grid mixes the following comparison was done. The environmental impacts of Icelandic geothermal power, Icelandic hydropower, Icelandic power grid mix, average European grid mix (UCTE – Union for the Co-ordination of Transmission of Electricity) and German power grid mix are shown in Figure 5-8. The UCTE-mix is set to 100 %. Basis for the comparison is the production of 1 kWh = 3,6 MJ each.

Impact categories:

- GWP (100 a) – Global warming potential (100 years)
- AP – Acidification potential
- EP – Eutrophication potential
- POCP - Photochemical oxidant creation potential
- HTP – Human toxicity potential
- AETP – Aquatic ecotocicity potential
- TETP – Terrestric ecotoxicity potential

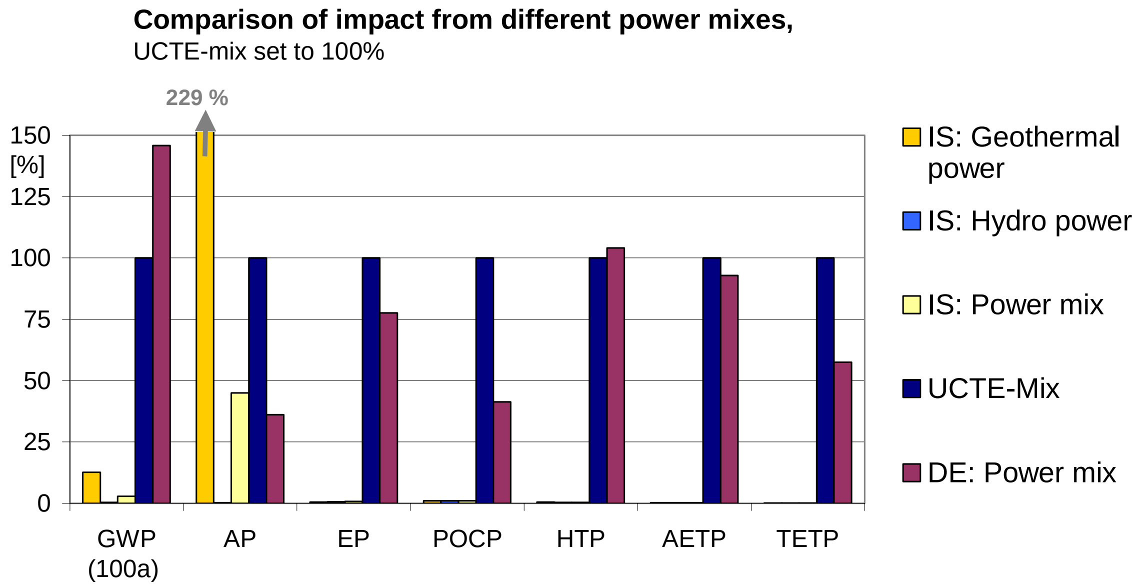


Figure 5-8: Comparison of environmental impacts of different power grid mixes

It can be seen in Figure 5-8 that in each category except AP the Icelandic power production produces very low environmental impact. The high value in the AP results of the H_2S-emissions within the geothermal power production. The level of the German power grid mix is mostly lower than of the UCTE-mix, which derives from the relatively strict emission limits. The lower GWP of the UCTE-mix in comparison to the German grid mix follows from the lower CO_2-emissions because of higher share of nuclear power. The contribution of different energy sources to the mentioned electricity mixes are shown in Table 5-7:

Table 5-7: Share of energy carriers in performed grid mixes

[%]	*IS: Geothermal power*	*IS: Hydro power*	*IS: Power mix*	*UCTE-Mix*	*DE: Power mix*
Geothermal power	100,0	-	18,1	-	-
Hydro power	-	100,0	81,9	8,5	4,1
Wind power	-	-	-	0,2	0,3
Biomass	-	-	-	0,2	0,1
Nuclear power	-	-	-	36,4	36,0
Lignite	-	-	-	11,9	27,7
Hard Coal	-	-	-	15,5	25,2
Natural Gas	-	-	-	9,7	5,6
Fuel oil	-	-	-	17,6	0,5
Waste incineration	-	-	-	0,0	0,5

Graphic accounts are also given in chapter 3.2.3 and 3.2.4 in Figure 3-5 and Figure 3-6.

H_2S-EMISSIONS IN ICELANDIC GRID MIX

H_2S as non-condensable gas is emitted from most of the high-temperature fields prior to their development. Fumaroles are also possible sources. With the installation of a power plant the produced fluid will exceed the natural emission from the field in most of the cases. A short overview regarding the fields in Iceland is given in Table 5-8.

Table 5-8: Hydrogen sulfide emission (in 1996) from exploited geothermal fields in Iceland (compiled by the authors) [28]

Geothermal field	*H_2S emission from fumaroles [t/a]*	*H_2S emission from produced steam [t/a]*	*Total H_2S emission [t/a]*	*[%] of total*
Reykjanes	5	60	65	1,0
Svartsengi	15	170	185	2,8

Geothermal field	***H_2S emission from fumaroles [t/a]***	***H_2S emission from produced steam [t/a]***	***Total H_2S emission [t/a]***	***[%] of total***
Nesjavellir	140	1880	2020	31,0
Námafjall	470	1300	1770	27,1
Krafla	700	1600	2300	35,3
Hveragerđi	140	40	180	2,8
Total	1470	5050	6520	100

In most of the cases, the emission from fumaroles at a geothermal field increases with its development as the fluid, pressure and temperature levels are changed. Those emissions are listed in the table as well as the ones directly related to the steam production for power generation or district heating.

An overview for Iceland regarding the annual discharge of H_2S is given in Figure 5-9. The natural discharge is twice as much as the one from geothermal power plants.

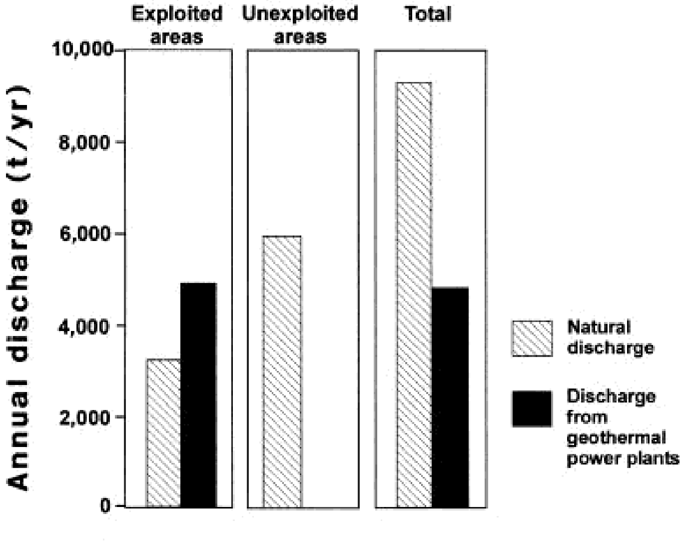


Figure 5-9: Annual discharge of H_2S from geothermal fields in Iceland [28]

There is another point to mention, regarding the environmental aspects of sulphur gas emissions. It is the possible conversion of H_2S to SO_2, which can cause acid rain. It is stated in [28] that this conversion is minor, or at least very slow, at atmospheric conditions in Iceland. In addition, the H_2S gas can be converted into sulphur that may then react with the soil to form sulphates like gypsum, which is not harmful for the environment.

In general, the processes in developed geothermal fields are quite complex and therefore not further discussed in this report. It is just stated that the H_2S emission is related to the Icelandic country due to its geological structure and the additional emission from the power plants should be considered on this background.

Appendix F Scenario

In the following the change of Icelandic fuel supply for road transport from a conventional to a hydrogen based is analysed. This gives an overview on the potential changes related to potential future hydrogen society.

The scenario was performed in 2003 as basis for further work in the ECTOS project.

CONVERSION OF ICELANDIC ROAD TRANSPORT TO A HYDROGEN BASED ONE

In the following scenario it is assumed that the total amount of gasoline and diesel that is “burned” in public and private transportation is substituted by hydrogen and fuel cell technology.

First of all, the H_2 demand for road transport is calculated based on the gasoline and diesel consumption in 2000 as listed in Table 5-9. Exploited energy is calculated from figures for the energy content of fuels and the efficiency of internal combustion engines.

Land transport Iceland - comparison

Gasoline / Diesel - amount and efficiency	Amount [tons] 1)	Energy content [MJ/kg] 2)	Energy usage [PJ]	Efficiency of engine [%] 3)	Exploited energy [PJ]
Gasoline for cars and machines	142.599	42,7	6,09	24%	1,46
Diesel for cars	47.463	43,5	2,06	24%	0,50
Diesel for work-vehicles and machines	61.885	43,5	2,69	24%	0,65
Gasoline and diesel in total	251.947		10,85		**2,60**

Hydrogen - amount and efficiency	Amount [tons] 1)	Energy content [MJ/kg] 2)	Energy usage [PJ]	Efficiency of engine [%] 3)	Exploited energy [PJ]
Energy need (exploited energy of Gasoline/diesel)					**2,60**
Efficency of H_2 FCs				37,7%	
Needed engergy content of H_2 (according to efficiency of FCs)			6,90		
Energy content of H_2		120			
Needed amount of H_2	57.536				

Electricity needed for H_2 production (61,4kWh/kg 4) assumed)	3.533	GWh	(averaged operating hours calculated for Icelandic grid 2001)
Required additional power plant capacity (6175h/a assumed)	572	MW	

1) Orkustofnun: Orkumál 2000 (The National energy authority Iceland: Energy forecast 2000)
2) IKP GaBi 4 software for Life Cycle Engineering
3) Wurster, R.: Brennstoffzellen in Kraftfahrzeugen. Schülerforum Umwelttechnik. L-B-Systemtechnik GmbH, September 2001
4) Norsk Hydro Electrolysers: Appendix A: ECTOS Fuelling Station Description

Table 5-9: Land transport Iceland, fossil fuel figures and calculations for conversion to Hydrogen

The reverse calculation is done for the H_2 demand. Starting with the exploited energy 2,6 PJ, dividing through assumed efficiency for engine with fuel cell drive (in this case for a passenger car not a bus) and energy content of H_2 results in a total amount of approx. 57.500 tons of H_2 that has to be produced to feed the fleet in Iceland.

The total emission and the energy demand for the production of the necessary amount of H_2 is calculated from the inventory data. As water is the main output from FC vehicles no additional emission is caused throughout the utilisation phase due to energy conversion of the consumed fuel.

The emission figures for the production of fossil fuels for the road transport represents the actual situation in Iceland and is based on inventory data for diesel and gasoline from an average European refinery. The emission in kg/kg_{Diesel} and the energy demand are multiplied with the fossil fuel consumption for road transport in the year 2000. In addition to these emissions from the manufacturing phase, emissions from the utilisation of the vehicles must be taken into consideration.

Values for CO_2, SO_2 and NO_x emissions from the transport sector in Iceland are given in [21]. The values for carbon monoxide (CO), hydro carbons (HC) and particulate matter (PM) had to be calculated and are based on the following assumptions:

1) It is assumed that the vehicles related to the term ‘gasoline for cars and machines’ in Table 5-9 fulfil either the emission limit EURO II or EURO III for passenger cars.
2) A share of 50 % of the vehicles per limit is assumed.
3) The CO and HC emission from burning the total amount of gasoline in these cars and machines is calculated by multiplying the total amount of NO_x emissions with an average emission factor for each emission. Those factors are derived from the emissions relation to the NO_x emissions.

Calculations for the diesel cars and work-vehicles are carried out similar to the above mentioned calculation. The necessary assumptions are that the diesel cars have averaged emissions based on the limits the EURO II and III for passenger diesel cars. Emission limits according to EURO II-III (commercial vehicles etc.) are taken for the other vehicles that consume diesel.

The emission factors are weighted according to the mass of fuel consumed (see Table 5-9). This leads to a factor for HC, CO and PM that is multiplied with the amount of NO_x that is emitted. The calculation finally results in a total HC, CO and PM emission figure for the road transport in Iceland (use) that is listed in Table 5-10.

Emission from production (total)			Emission from road transport Iceland (use)[1]	Emission from production + use phase
[kg]	Gasoline	Diesel	**[kg]**	**[kg]**
Carbon dioxide	79.755.160	41.015.363	786.000.000	906.770.523
Carbon monoxide	98.738	68.721	*9.246.479*	9.413.938
Sulphur dioxide	421.008	198.043	360.000	979.051
Hydrogen sulphide	652	466	---	1.118
Nitrogen oxides	333.332	217.918	6.250.000	6.801.250
NMVOC into air	1.187.774	860.745	*5.268.875*	8.086.702
Methane	443.340	325.967		
Particulate matter	44.796	26.129	*179.362*	250.286
Energy (net calorific value), total [MJ]	7.309.698.532	5.448.864.015		12.758.562.547

[1] Statistical Year Book Iceland 2002. Chapter 1: Environment (cursive figures are calculated)

Table 5-10: Emissions from production and use of fossil fuels for road transport in Iceland (per year)

The emissions related to production and “use” of the respective amounts of fuel are summed up and the difference between those emissions and the ones from the production of an equivalent amount of H_2 is calculated. The reduction potentials are shown in Figure 5-10.

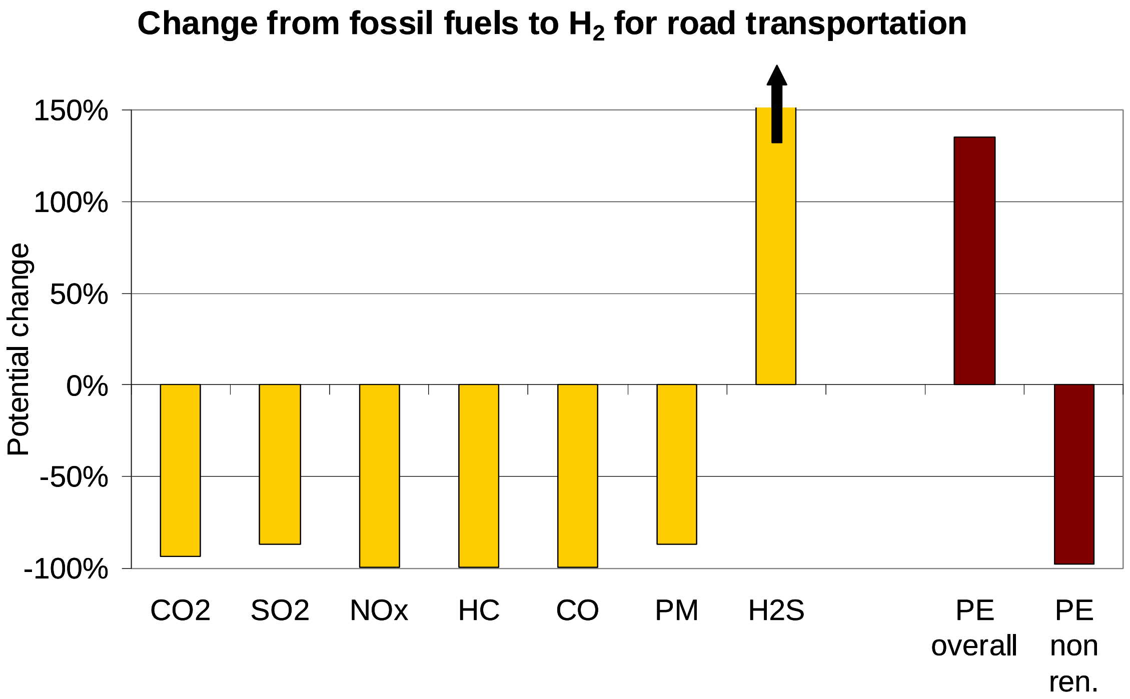


Figure 5-10: Emission reduction potentials from conversion of road transport based on fossil fuels to hydrogen

All emissions except H_2S are dramatically reduced by this conversion from fossil fuel based road transport to a H_2 based one. The high H_2S emission is closely related to the geothermal power generation related to the power demand for the H_2 production process. H_2S is no main emission from diesel or gasoline driven vehicles and the amount emitted at refineries is quite low. More information on H_2S in Iceland can also be found in [28] and Appendix E.

ENERGY DEMAND

The total primary energy demand is higher for the H_2 alternative Figure 5-10 but the primary energy demand from non-renewable sources is reduced. This leads towards considerations that are related to the power supply.

In case of H_2 based transportation the power demand increases. The last in Table 5-9 show the calculated additional power supply that is required for the production. Additional 3.500 GWh would be required. Based on the assumption that hydropower would be the technology of choice, one additional 572 MW power plant would be necessary.

New power plants have to be build to meet the increasing demand. Additional capacity in the form of hydro or geothermal power plants could be installed. The decision for one of those types is in a way dependant on the 'installation speed' [43]. In case that the new capacity has to be installed in one step, it is most likely that hydro power plants will be built. When the road transport conversion towards H_2 is done in smaller steps, the required additional capacity could be realised with geothermal power plants of 30 to 90 MW. The reason is, according to [43], that it is risky to build geothermal power plants in on big step (natural boundary conditions) and on the other hand that it is relatively costly to install small hydro power stations.

In general it can be assumed that the ratio between hydro and geothermal power will not be very different from the actual one although the harnessing of geothermal power was increasing during the last years.

CALCULATION OF EMISSION FACTORS FOR SCENARIO

The total amount of HC, CO and PM emission from Icelandic road transport were not available. Therefore, factors were calculated for those emissions based on the limit values for passenger cars (Otto and Diesel engine) and diesel trucks. Therefore, the given figures for HC, CO and PM emissions should be seen as a first estimation.

The assumed fleet consists of cars and trucks that fulfil the Euro II and III exhaust gas limits.

Table 5-11: Calculation of factors for road transport emissions (HC, CO, PM) for scenarios

Exhaust gas limits (passenger cars with otto engine)			
[g/km]	Otto Euro II	Otto Euro III	Average Euro II & III
CO	2,70	2,30	2,50
HC	0,34	0,20	0,27
NOx	0,25	0,15	0,20
PM	---	---	
Calcualated ratios:			
HC/NOx	1,360	1,333	1,347
NOx/CO	0,093	0,065	0,079
PM/NOx	---	---	
Exhaust gas limits (passenger cars with diesel engine)			
[g/km]	Diesel Euro II	Diesel Euro III	Average Euro II & III
CO	1,06	0,64	0,85
HC	0,204	0,08	0,14
NOx	0,566	0,5	0,53
PM	0,08	0,05	0,07
Calcualated ratios:			
HC/NOx	0,360	0,160	0,260
NOx/CO	0,534	0,781	0,658
PM/NOx	0,141	0,100	0,121
Exhaust gas limits (commercial vehicles/trucks with diesel engine)			
[g/km]	EURO III Norm	EURO II Norm	Average Euro II & III
CO	2,1	4	3,05
VOC	0,66	1,1	0,88
NOx	5	7	6,00
PM	0,1	0,2	0,15
Calcualated ratios:			
HC/NOx	0,132	0,157	0,145
NOx/CO	2,381	1,750	2,065
PM/NOx	0,020	0,029	0,024

Table 5-12: Ratio of different vehicles on the road transport in Iceland according to the mass of fuel consumption

Fossil fuel demand for road transport in Iceland per 'category'		Assumed emission according to limits for
Gasoline for cars and machines	57%	passenger car with otto engine
Diesel for cars	19%	passenger car with diesel engine
Diesel for work-vehicles and machines	25%	commercial vehicle/truck

The emission factors in Table 5-13 are calculated from the ratio of the different vehicle types in Iceland (road transport) and the average emission factors calculated per vehicle type (figures in last column of Table 5-11).

Table 5-13: Calculated and averaged emission factors for HC, CO and PM from Icelandic road transport

Calcualated emission factors:		
Factor for HC	= 0,57*1,347 + 0,19*0,260 + 0,25*0,145	0,853
Factor for CO	= 1/(0,57*0,079 + 0,19*0,658 + 0,25*2,065)	1,457
Factor for PM	= 0,19*0,121 + 0,25*0,024	0,029

The result of all those calculation is displayed in Table 5-14.

Table 5-14: Total amount of annual emission from road transport in Iceland, HC, CO and PM figures are calculated

Emissions from road transport in Iceland 2000 (Source: Statistical Year Book Iceland 2002, Chapter 1) in tons	
CO_2	786.000
SO_2	360
NOx	6.250
HC (calculated from NOx*Emission factor HC)	5.269
CO (calculated from NOx*Emission factor CO)	9.246
PM (calculated from NOx*Emission factor PM)	179

Appendix G Characterisation factors for impact categories

The characterisation factors for the used impact categories are developed by:

CML
Institute of Environmental Sciences, Leiden University, Netherlands
http://www.leidenuniv.nl/interfac/cml/ssp/index.html

and can be downloaded as table from:

http://www.leidenuniv.nl/cml/ssp/projects/lca2/index.html

For more information also see the methodology report [24] and the GaBi 4 software documentation and manual [23].

In the following characterisation factors for Global Warming Potential (100 years) and Acidification Potential according to CML 2001 [5] are listed as examples.

CHARACTERISATION FACTORS FOR GLOBAL WARMING POTENTIAL (100 YEARS)

Table 5-15: Characterisation Factors GWP (100 years), CML 2001 [5]

CML2001, Global Warming Potential (GWP 100 years)	***1 [kg] = XXX [kg CO_2-Equiv.]***
Carbon dioxide	1
Carbon tetrachloride (tetrachloromethane)	1800
Chloromethane (methyl chloride)	16
Dichloromethane (methylene chloride)	10

CML2001, Global Warming Potential (GWP 100 years)	***1 [kg] = XXX [kg CO_2-Equiv.]***
Halon (1211)	1300
Halon (1301)	6900
Methane	23
Methyl bromide	5
Nitrous oxide (laughing gas)	296
Perfluorobutane	8600
Perfluorocyclobutane	10000
Perfluorohexane	9000
Perfluoropentane	8900
Perfluoropropane	8600
R 11 (trichlorofluoromethane)	4600
R 113 (trichlorofluoroethane)	6000
R 114 (dichlorotetrafluoroethane)	9800
R 115 (chloropentafluoroethane)	7200
R 116 (hexafluoroethane)	11900
R 12 (dichlorodifluoromethane)	10600
R 12 (dichlorodifluoromethane)	10600
R 12 (dichlorodifluoromethane)	10600
R 123 (dichlorotrifluoroethane)	120
R 124 (chlorotetrafluoroethane)	620
R 125 (pentafluoroethane)	3400
R 13 (chlorotrifluoromethane)	14000
R 134	1100

CML2001, Global Warming Potential (GWP 100 years)	***1 [kg] = XXX [kg CO_2-Equiv.]***
R 134a (tetrafluoroethane)	1300
R 141b (dichloro-1-fluoroethane)	700
R 142b (chlorodifluoroethane)	2400
R 143 (trifluoroethane)	330
R 143a (trifluoroethane)	4300
R 152a (difluoroethane)	120
R 22 (chlorodifluoromethane)	1700
R 225ca (dichloropentafluoropropane)	180
R 225cb (dichloropentafluoropentane)	620
R 227ea (septifluoropropane)	3500
R 23 (trifluoromethane)	12000
R 236fa (hexafluoropropane)	9400
R 245ca (pentafluoropropane)	640
R 32 (trifluoroethane)	550
R 41	97
R 43-10 (decafluoropentane)	1500
Sulphur hexafluoride	22200
Tetrafluoromethane	5700
Trichloroethane	140
Trichloromethane (chloroform)	30

CHARACTERISATION FACTORS FOR ACIDIFICATION POTENTIAL

Table 5-16: Characterisation Factors AP, CML 2001 [5]

CML2001, Acidification Potential (AP)	***1 [kg] = X,XX [kg SO_2-Equiv.]***
Ammonia	1,88
Ammonium	3,76
Ammonium nitrate	0,85
Hydrogen bromine	0,40
Hydrogen chloride	0,88
Hydrogen fluoride	1,60
Hydrogen sulphide	1,88
Nitric acid	0,51
Nitrogen dioxide	0,70
Nitrogen monoxide	1,07
Phosphoric acid	0,98
Sulphur dioxide	1,00
Sulphur trioxide	0,80
Sulphuric acid	0,65