Deliverable 5.1:

Initial LCA results on the “base case” HELMETH concept system

PROJECT & ACRONYM:	Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion (HELMETH)
TYPE OF PROJECT:	Collaborative project; Co-financed by the European Union's Seventh Framework Programme for the Fuel Cells and Hydrogen Joint Technology Initiative
GRANT AGREEMENT NO.:	621210

TYPE OF DOCUMENT:	DELIVERABLE
LEAD BENEFICIARY:	NTUA
CONTRIBUTORS:	DVGW, SUNFIRE
FILE NAME:	HELMETH_DEL_5_1_R_2.2.docx
RELEASE:	R.2.2
DATE:	27/11/2015
ABSTRACT:	A thorough environmental assessment of a “base case” configuration of the innovative HELMETH concept system.

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Glossary

Abbreviation / acronym	**Description**
P2G/ PtG	Power-to-Gas
SNG	Substitute/Synthetic Natural Gas
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
H_2	Hydrogen
CO	Carbon monoxide
CH_4	Methane
H_2O	Water
PED	Primary Energy Demand
NTP	Normal Temperature and Pressure

Project partner acronyms	
KIT	Karlsruhe Institute of Technology
POLITO	Politecnico di Torino
SUNFIRE	Sunfire GmbH
ERIC	European Research Institute of Catalysis A.I.S.B.L.
EEI	EthosEnergy Italia
NTUA	National Technical University of Athens
DVGW	DVGW - German Technical and Scientific Association for Gas and Water

1. Executive summary

This deliverable is part of the HELMETH project, which is devoted to a proof of concept of a highly efficient Power-to-Gas (P2G) technology with methane as a chemical storage and by thermally integrating high temperature electrolysis (SOEC technology) with methanation.

Deliverable 5.1 presents the initial environmental Life Cycle Assessment (LCA) of the "base case" HELMETH concept system, by investigating the environmental and energetic impacts in terms of CO2 emissions from fossil fuel sources. The analysis refers to a "cradle-to-gate" approach, referring to the production of 1 m^3 of Synthetic Natural Gas, according to the preliminary simulations presented in the DoW. The first step is to properly define the "base case" scenario of HELMETH system, which will be the reference case to the following deliverable, when a comparative LCA against benchmark scenarios will be carried out.

Assuming a strong trend towards renewable generation and the utilization of CO_2 output of a biomethane plant shows two environmental advantages: (a) the potential of a "fossil PED sink effect", since more fossil PED is avoided than consumed and (b) an output flow of SNG made by biogenic carbon, thus providing no fossil CO_2 emissions in the next stages of utilizing (burning) the SNG (not shown in the present analysis).

Existing open issues (such as pressurization of CO_2 from bio-CH_4 output to the pressure requested by the HELMETH system, potential utilization of the produced O_2) and planned forthcoming steps (incorporation of the impact caused by the manufacturing and assembly of the system, comparison to benchmark electricity storage systems, investigation of alternative CO_2 sources) are to be addressed in the following stages of WP5.

The environmental assessment is based on the ILCS Handbook and the "FC-HyGuide" Guideline document, while the LCA approach is carried out according to ISO 14040-43.

2. Introduction

2.1. Background

The report at hand was elaborated within the Work Package 5 "LCA, Market and Socioeconomic Studies" in the HELMETH project (*Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion*). The main objective of the HELMETH project is the proof of concept of a highly efficient Power-to-Gas (P2G) technology with methane as a chemical storage and by thermally integrating high temperature electrolysis (SOEC Technology) with methanation.

The LCA method aims to investigate and compare environmental impacts of products or services that occur along their supply chain from cradle to grave. The method is standardized by the International Organization for Standardization (ISO).

Within the HELMETH project, the Life Cycle Analysis will be performed for the overall process against benchmark scenarios. For each scenario the impact of CO_2 sources on the system's CO_2 footprint will be evaluated.

This study focuses on the "base case" scenario: a thorough environmental assessment of the "base case" configuration of the innovative HELMETH concept system will be performed, in order to quantify its environmental advantages. The environmental assessment will be performed by NTUA in accordance with the ILCD Handbook and the "FC-HyGuide" Guideline document. A life cycle approach will be followed, according to ISO 14040 – 43. The study will evaluate each component in the "base case" scenario, regarding material composition, production processes and supply of fuel to the system, including evaluation of the life cycle energy efficiency of the system.

2.2. Goal & Scope

This study aims to assess the environmental impact of the "base case" configuration of the innovative HELMETH concept system, in order to quantify its environmental advantages. The specific objectives are:

- To establish a baseline of the overall resource use, energy consumption and environmental loadings of a "base case" scenario
- To identify critical materials/processes/operational parameters, whose effect is critical towards improving the environmental impact of the system's life cycle (construction / operation / end of life)
- To assess the life cycle environmental performance of the "base case" scenario
- To assess the life cycle CO_2-eq impact of the alternative CO_2 sources (in the next level of analysis)

2.3. Functional unit and geographical scope

The primary service provided by all systems is a quantity of power production, and hence the specified functional unit delivered by all alternative systems will be the production of 1m^3 (NTP) of CH_4.

The systems are geographically and technologically represented by northern European conditions (mainly Germany). Moreover, the correlated heat and power systems are represented by the various heat and power technologies found within Germany. Note that the power production used in the models refers to projections of the average generation mix on the German grid. The time frame has been set from 2020 to 2050, when the P2G concept is expected to reach the maturity needed for actual applications. Processes that have less significance derive from the Ecoinvent database. The most recent data are used for all parts of the systems and if possible data are projected to represent a near term future.

3. Overview of the "base case" scenario

The stand-alone concept for renewable power to methane production is very attractive for countries with high natural gas import dependence and vast remote renewable resources. Wind, solar, hydro power or bioenergy plus water for electrolysis and CO_2 either extracted from air or captured from a biogas plant or similar, are sufficient to produce a natural gas substitute.

In order to proper define the "base case" scenario of the HELMETH system, all possible options/alternatives should be identified. The choice of the final "base case" scenario is based on the criteria that cover the following areas:

- Estimated techno-economic feasibility
- Estimated environmental advantage
- Current practice in running PtG research

The different parameters that comprise various options regard:

- Electricity supply
- CO_2 supply
- SNG output
- Nominal output power of concept system

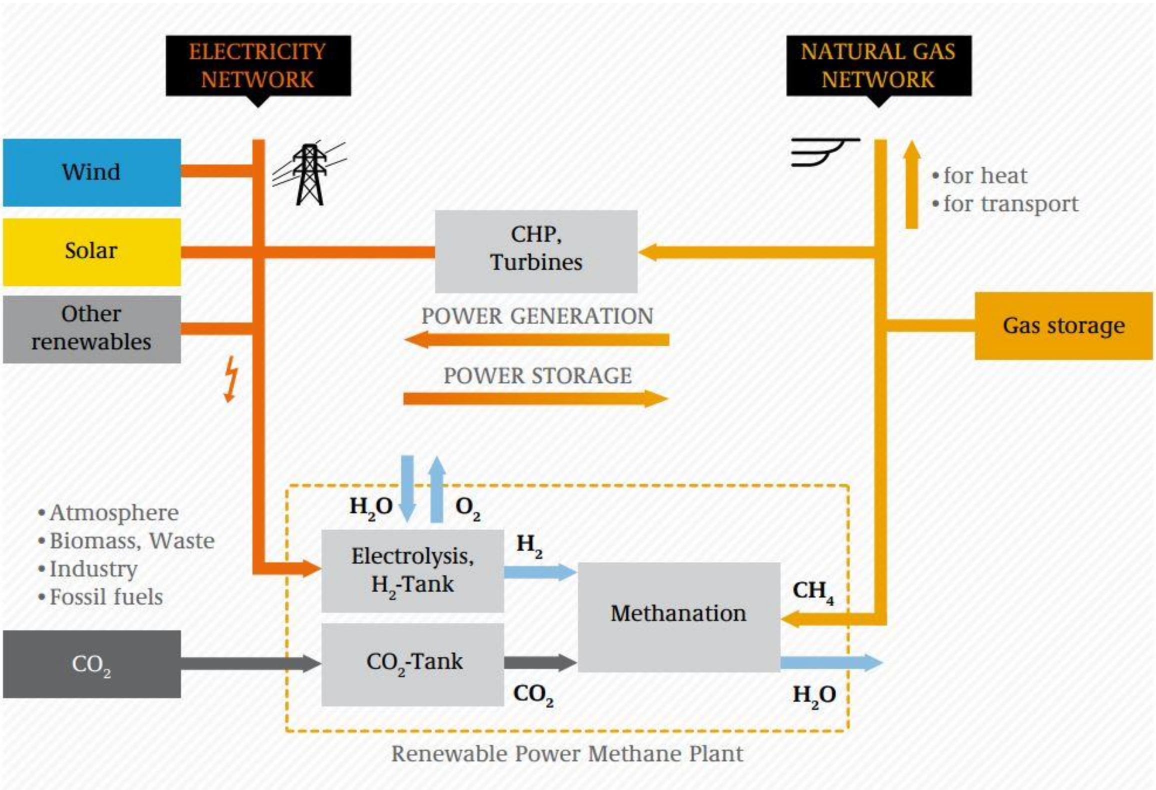

Figure 1: Concept for the transformation of excess electricity from RES via hydrogen to methane (SNG) with reconversion in combined heat and power plants, gas turbines or combined cycle power plants (Sterner, 2009)

3.1. Electricity Supply

In the current global development of sustainable energy resources, a new storage need for electricity produced from renewable sources is rising. It is widely known that wind and solar plant production periods heavily depend on the weather conditions and are characterized by intermittent operation: high daily and seasonal fluctuation. In order to maintain and increase the share of renewables in the energy mix, storage solutions must be implemented in order to satisfy the demand.

For the "base case" scenario needs, direct connection to the electricity grid is assumed. The reason for the selection of this option is based on many parameters. Compared to a direct connection to a wind or PV plant, this option is characterized by higher utilization factor and fewer starts/stops on a daily or seasonal period. Moreover the SOEC degradation is lower and finally, proximity problems to CO_2 supply plants and/or SNG grid injection near the Wind/PV plants are solved.

3.2. CO_2 Supply

The power-to-gas concept uses external carbon. CO_2 is a waste product of many different processes (see ***Figure 2***) and the emission sources are present in three main areas: fuel combustion activities, industrial processes and natural gas processing. The largest CO_2 emissions by far result from the oxidation of carbon when fossil fuels are burned. These emissions are associated with fossil fuel combustion in power plants, oil refineries and large industrial facilities. Carbon dioxide not related to combustion is emitted from a variety of industrial processes which transform materials chemically, physically or biologically. Such processes include:

- the use of carbon as a reducing agent in the commercial production of metals from ores (IPCC,2001);
- the thermal decomposition (calcination) of limestone and dolomite in cement or lime production (IPCC 2001);
- the fermentation of biomass (e.g., to convert sugar to alcohol).

In some instances these industrial-process emissions are produced in combination with fuel combustion emissions, a typical example being aluminium production (IPCC Working Group, 2005).

A third type of source occurs in natural-gas processing installations. CO_2 is a common impurity in natural gas, and it must be removed to improve the heating value of the gas or to meet pipeline specifications (IPCC Working Group, 2005).

Process	CO_2 concentration in gas stream % by vol.	Number of sources	Emissions ($MtCO_2$)	% of total CO_2 emissions	Cumulative total CO_2 emissions (%)	Average emissions/source ($MtCO_2$ per source)
CO_2 from fossil fuels or minerals						
Power						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels[a]	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
Natural-gas sweetening						
	NA[b]	NA	50[c]	0.37	79.16	
Cement production						
Combined	20	1175	932	6.97	86.13	0.79
Refineries						
	3 to 13	638	798	5.97	92.09	1.25
Iron and steel industry						
Integrated steel mills	15	180	630[d]	4.71	96.81	3.50
Other processes[d]	NA	89	16	0.12	96.92	0.17
Petrochemical industry						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
Other sources						
Non-specified	NA	90	33	0.25	100.00	0.37
		7,584	**13,375**	**100**		**1.76**
CO_2 from biomass[e]						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			**0.2**

Figure 2: Profile of worldwide large CO_2 stationary sources (Source: IEA GHG, 2002a).

The waste CO_2 of a biogas upgrading process would be an interesting source for CO_2. The small share of CH4 which is together with the CO_2 as a part of the waste gas would make the methanation process more efficient.

As presented in ***Figure 3***, another parameter that should be taken into account, when trying to define the "base case" scenario is the input flow of CO_2 from each plant. For the HELMETH system, a biogas plant provides the necessary input flow of CO2, that covers the needs of methanation.

For the definition of the "base case" scenario and in order to ensure this input flow, proximity to a biogas plant is assumed. The reasons for this selection are summarized here:

- Biogenic carbon input
- High CO_2 content (40% vol.) compared to flue gas
- Preferred CO_2 source in all running PtG research projects (According to (DGTC, 2013))

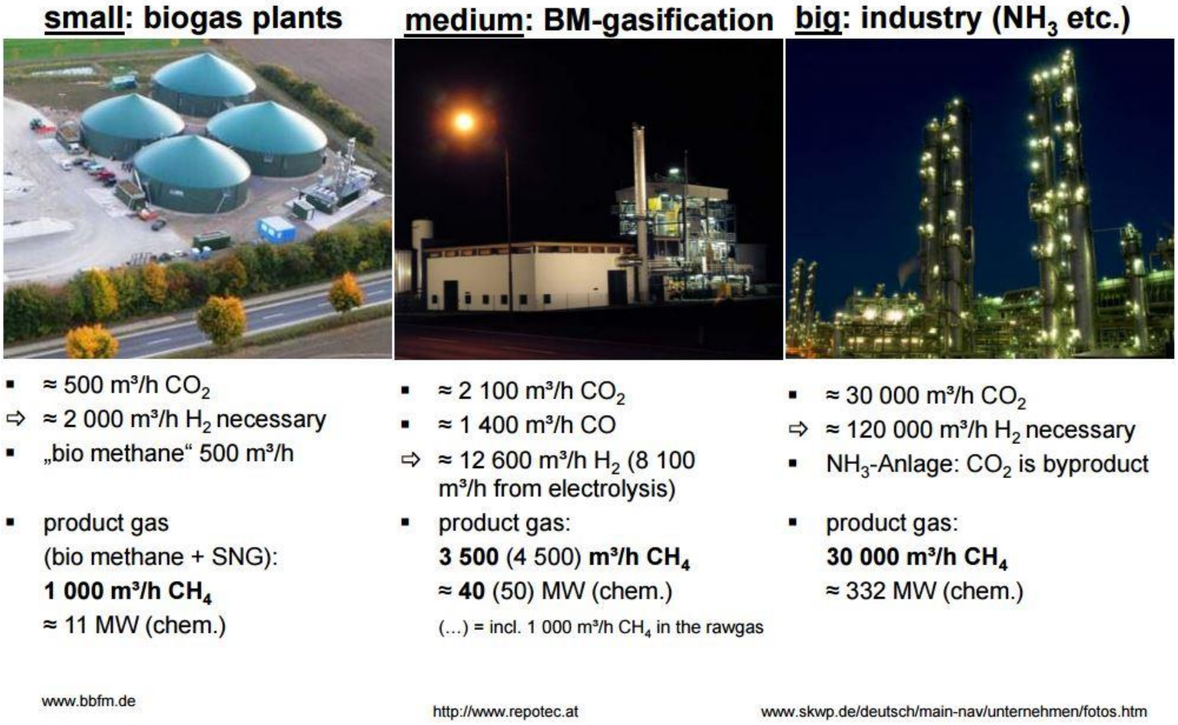

Figure 3: Possible CO/CO_2 sources for PtG (Bajohr, 2013)

3.3. SNG Output

Another crucial issue that needs to be addressed for the LCA scenarios is the pathway for the production of SNG. The renewable natural gas substitute (SNG) can be stored, distributed and reconverted on demand in balance power e.g. in gas turbines or combined cycle power plants. For this, SNG has to be directly injected into the NG grid. Crucial parameter is the proximity of the PtG facility to the NG grid or not.

For all scenarios examined in terms of LCA, injection to the NG grid will be assumed.

3.4. Nominal output power of concept system

A wide range of different technologies exists to store electrical energy. Different applications with different requirements demand different features from electrical energy storage (EES). A general overview of EES is given in ***Figure 4*** (IEC, 2010). Clearly PHS, CAES, H_2 and SNG are the only storage technologies available for high power ranges and energy capacities, although energy density is rather low for PHS and CAES. Only PHS is mature (***Figure 5***) (IEC, 2010), however severe restrictions in locations (topography) and land consumption are considered as important limitations. Single components of SNG storage systems are available and in some cases have been used in industrial applications for decades. For long discharge times, days to months and huge capacities (GWh - TWh), only chemical secondary energy carriers can be considered (H_2, SNG), which can be created from various renewable energy sources. In addition, the chemical secondary energy carriers can be used in other application areas, such as in transport.

There are two options for the nominal output power of the system that will also define the alternative conventional systems: a nominal power of ~10MW or ~100MW of electricity storage can be assumed. The competitive technologies for the first range are the flywheels and the batteries, while for the second the technologies are a reversible hydroelectric plant (PHS) or Compressed air energy storage (CAES). In the current study, e.g. a nominal power of ~10MW of electricity storage is assumed, as a consequence of the assumption of the connection of the HELMETH system to a biogas plant (see subchapter 3.2).

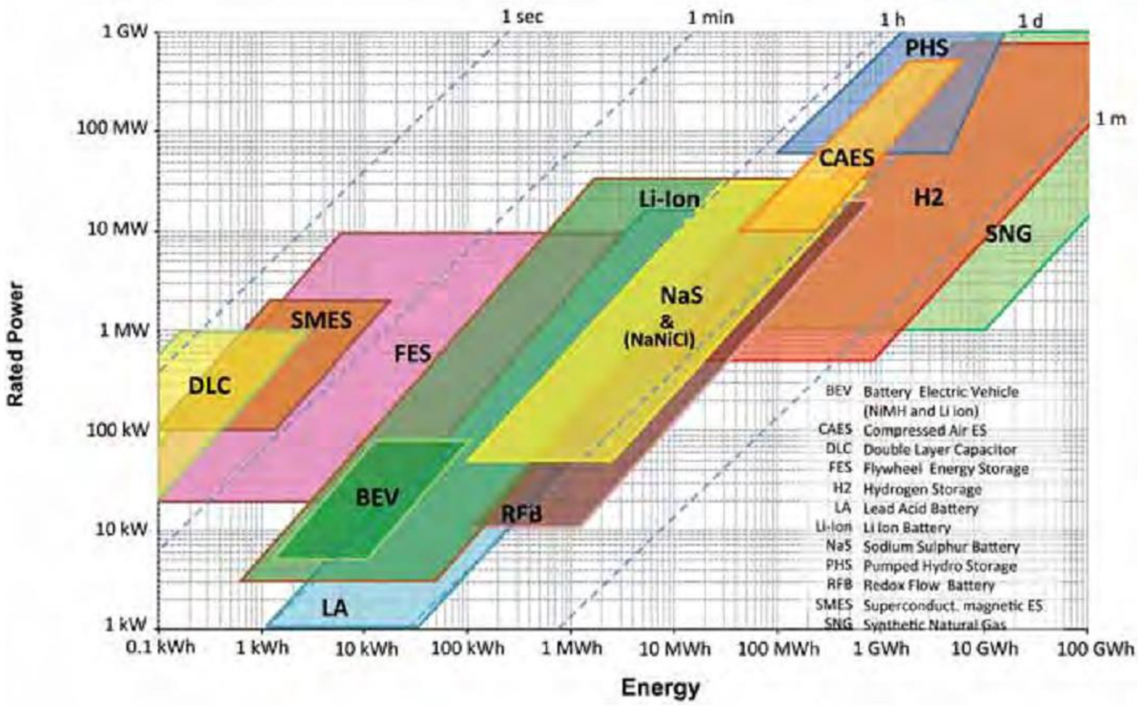

Figure 4 Comparison of rated power, energy content and discharge time of different EES technologies. (IEC, 2010)

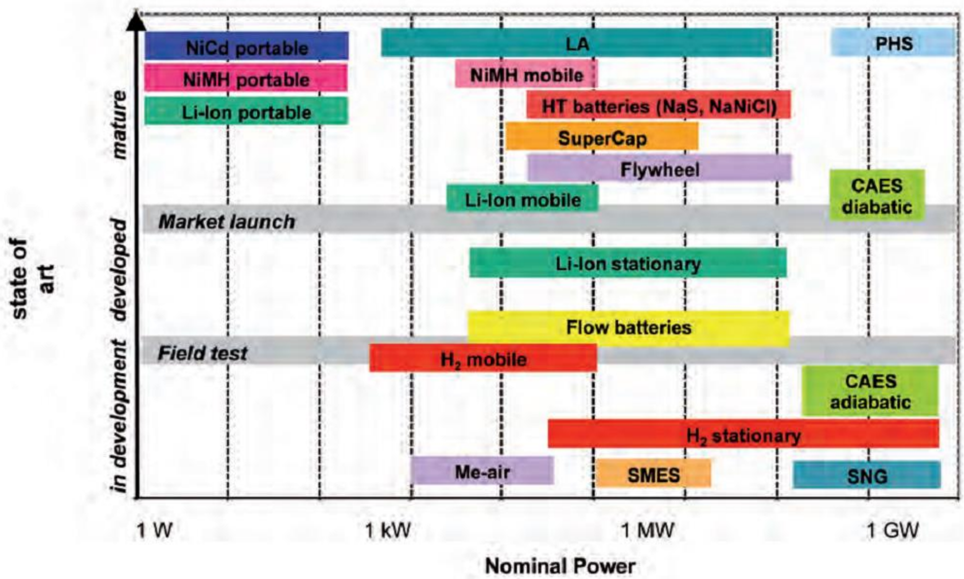

Figure 5: Maturity and state of the art of storage systems for electrical energy (IEC, 2010)

4. Life Cycle Inventories: Summary

In this Chapter, a summary of the modelled life cycle inventories is given. The boundaries in the modelling include the whole HELMETH system (considered as black box), focusing on the inputs and outputs (see ***Figure 6***). The preliminary mass/energy balance presented in ***Figure 7*** is based on simulation results provided in the DoW of HELMETH (pg. 51, 58, 59).

The by-products of the whole process (O_2 and H_2O) can be considered as potentially useful. The Ecoinvent database provides data regarding the production of liquid oxygen, it has however not been considered as "avoided product", due to the uncertainty regarding the feasibility of the relevant utilization. The potential benefits of avoiding or recirculating water will be incorporated, if the contribution of the water inflow in respect to the results is significant.

The relevant values will be re-evaluated, according to the expected results of the simulation activities within the HELMETH work frame. Subchapters 4.1-4.3 describe the materials, fuels and electricity needed for the process, while subchapter 4.4 describes the by-product of the process. The full description of the life cycle inventories is presented in the Annex.

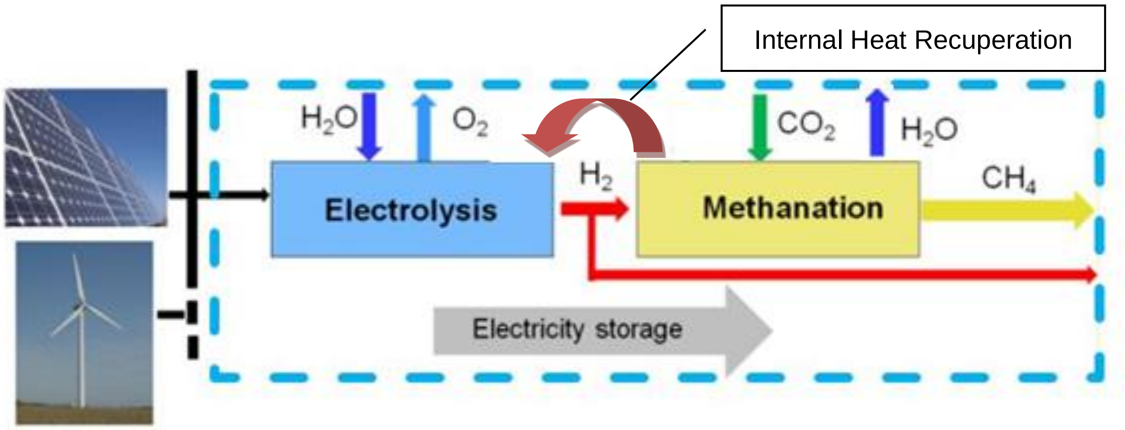

Figure 6: Boundaries of the life cycle modelling for the HELMETH system

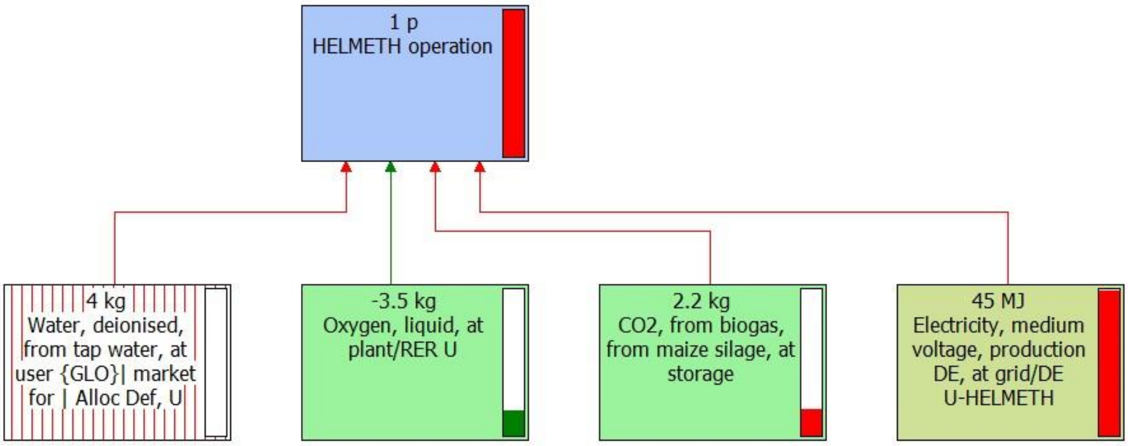

Figure 7: Preliminary mass/energy balance for the production of 1 m^3 of SNG (Source: DoW)

4.1. CO_2 input from biomethane plant using maize silage

Maize is one of the most commonly used energy crops in agricultural or industrial biogas production plants and therefore plays an important role for the evaluation of different substrates in anaerobic digestion. The choice of maize silage as the reference biomass substrate for biogas production is justified by its share of contribution not only in present (79% of renewable input for biogas in Germany for 2012 (Graf and Bajohr, 2013 -pg. 319)), but also in future terms (DVGW, 2013). Compared to other energy crops, the properties of maize silage are favourable for biogas production. The cultivation has no special requirements, the maize yield per hectare is comparably high, and the silage can easily be stored in bunker silos (Fachagentur Nachwachsende Rohstoffe, 2006). The biogas yield per ton maize silage depends on the variety. Varieties with late ripening produce more biogas than early ripening varieties (Amon et al., 2007, Fachagentur Nachwachsende Rohstoffe, 2006). A drawback of maize silage used in anaerobic digestion is its competitive use as animal feed (indirect food production) as well as this land usage might be/ is competitive to direct food production.

Experiences with maize in anaerobic digestion are available from biogas production in Germany, where maize is often added as a co-substrate. The agricultural production of maize has to be fully attributed to the environmental impact of the biogas production.

The LCI data on maize silage and biogas production (***Figures 8, 9***) are taken from (Graf and Bajohr, 2013 -pg. 383, 120), with additions form the Ecoinvent LCA database v3.0 (datasheet: "Maize silage, Swiss integrated production {CH}| maize silage production, Swiss integrated production, intensive | Alloc Def, U") (see Annex). A value of 65% of biomass-to-biogas energy efficiency was assumed, according to (DVGW, 2011 – pg.33) and (Stucki et al., 2011 - pg.16).

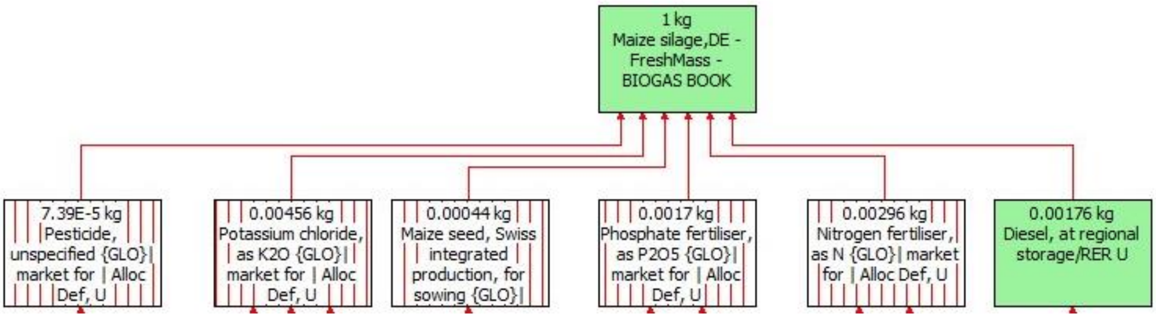

Figure 8 Input for the production of 1 kg of maize silage (Data source: Graf and Bajohr, 2013; Ecoinvent v3.0). Detailed data in Annex.

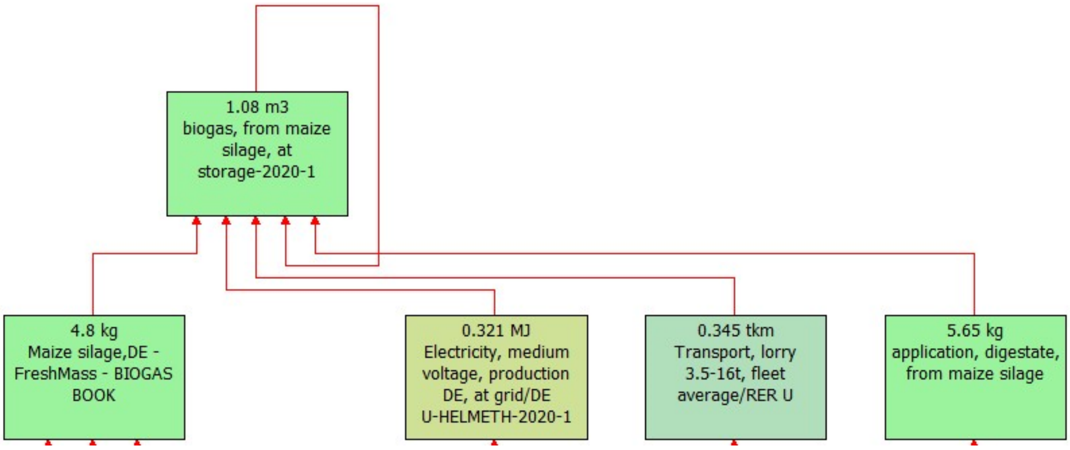

Figure 9 Input for the production of 1 m3 of biogas (Data source: Graf and Bajohr, 2013; Ecoinvent v3.0). Detailed data in Annex. *The recycle loop of biogas represents a 8% used internally for covering the heat demand of the anaerobic digester.

As regards the purification stage of biogas, the relevant LCI data (***Figure 10***) were taken from (Stucki et al., 2011), while the electric consumption was checked with (Graf and Bajohr, 2013), where an acceptable difference of ca. 15% was found. The produced bio-CH_4 has been assumed to replace the equivalent of natural gas import mix in Germany, thus introducing the corresponding environmental benefit. It has to be noted that the Pressure Switch Adsorption stage assumed provides a CO_2 stream at 5 bar (Graf and Bajohr, 2013), requiring additional pressurisation to 30 bar (as stated in the DoW simulations (pg. 58, 59)). The corresponding energy consumption has not been considered at the present state of analysis.

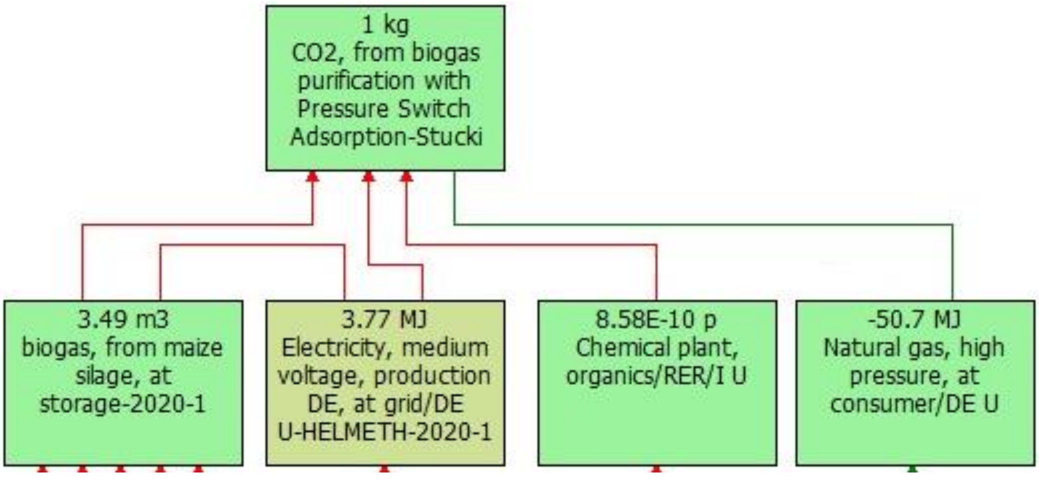

Figure 10 Input for the production of 1 m^3 of CO_2 from biogas through Pressure Switch Adsorption (Data source: Stucki et al., 2011 - pg.83). Electric demand checked with (Graf and Bajohr, 2013). Detailed data in Annex.

4.2. Water

The power-to-gas concept includes two production steps (see ***Figure 6***): the water electrolysis to produce hydrogen (H_2) and the methanation which uses CO_2 to create CH_4, and water. The water provided for the process is modelled by the datasheet "Water, deionised, at plant/CH U", modified

in terms of electric input. The potential benefits of avoiding or recirculating water will be incorporated, if the contribution of the water inflow in respect to the results is significant. The detailed LCI data are presented in the Annex.

4.3. Electricity

The electricity generation mix assumed as input to the operation of the HELMETH concept system has to reflect a future status, since a potential application cannot be considered feasible before 2025. Energy generation in Germany is shifting towards renewable sources, in order to achieve the target of the National Renewable Energy Action Plan (NREAP, 2009), aiming at a corresponding share of 38.6% in the electricity sector until 2020.

Three recent relevant studies (VDE-ETG, 2012; PROGNOS, 2014; OEKO, 2014) have been utilized in order to assess the evolution of the German generation mix in the following decades. The study of VDE-ETG considers not only the new renewable energy plants needed to reach a contribution of 80 % until 2050, but also corresponding storage facilities and grid stability issues.

Two electricity generation scenarios have been formulated (***Figure 11*** - Details in ***Table 1*** in Annex):

- Scenarios "2020" - Reference year: 2020

According to the studies utilized, three electricity generation share scenarios are built, all achieving the NREAP targets by featuring a renewable share of ca. 40%.

- Scenarios "2050" – Reference year 2050

The projections for the German generation mix for the year 2050 are the source of information for the corresponding "2050" scenarios. The renewable share lies between 80% and 100%.

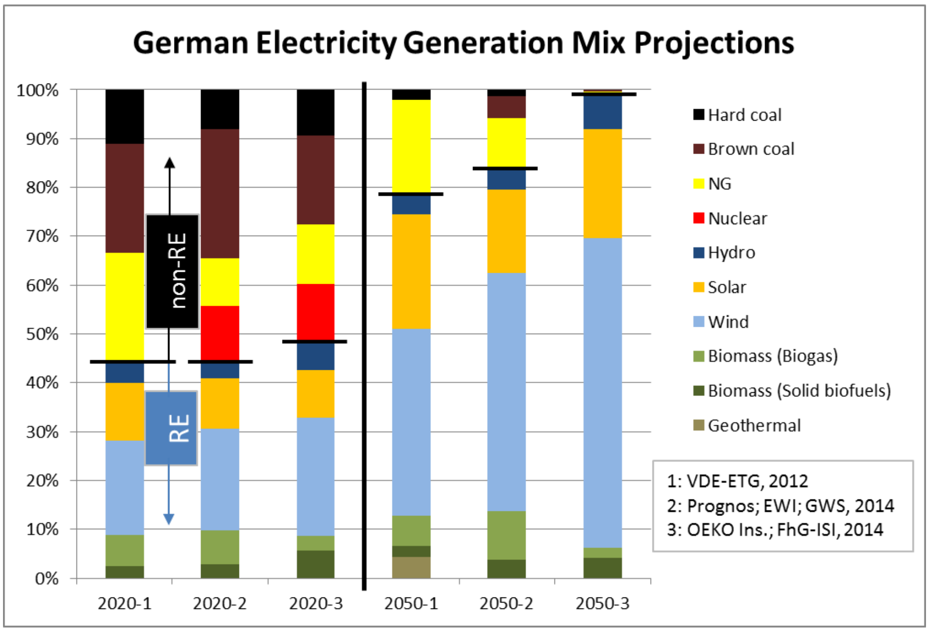

Figure 11 German Electricity Generation Mix Projections.

5. Life Cycle Impact Assessment

The inventories presented in Chapter 4 were used as data input to a specialized LCA software (SimaPro v. 8), in order to acquire results regarding:

- The fossil CO_2 emissions caused by the three input flows considered (Electricity, CO_2 and water)
- The Primary Energy Demand (PED) of the respective input flows, distinguished according to its origin (renewable – wind, solar, biomass, geothermal and non-renewable – fossil and nuclear).

5.1. Upstream emissions of fossil CO2

The fossil CO_2 index includes the corresponding upstream emissions caused by the three input flows considered. In other words, the present analysis refers to a "cradle-to-gate" approach. It is important to keep in mind that the emissions calculated refer to the production of 1 m^3 of Synthetic Natural Gas, as shown in the preliminary simulations presented in the DoW (pg. 51, 58, 59).

As expected, the electricity generation is responsible for the major part of the CO_2 emissions on the "2020" scenario (***Figure 12*** – left side), due to the share of the combustion of fossil fuels. In Scenario "2020-2", there may be almost equal shares of renewables, however the difference in the CO_2 emissions is explained by the absence of nuclear input in Scenario "2020-1". As regards the third study, it features an even more optimistic result. There is an insignificant contribution by the water supply flow.

The utilization of the CO_2 co-produced in a biomethane plant is associated to almost 2 kg of emissions per produced m^3 of SNG, which is explained in ***figure 13***. Nearly all the emissions come from the production of biogas (0.835 kg fossil CO_2/kg CO_2 input) and the electricity demand for the purification stage. A fair amount of emissions is avoided by displacing the corresponding supply of natural gas (due to the production of bio-CH_4). The contribution of the biogas production is caused by maize silage production (44% - mostly assigned to the production of Calcium Nitrate for the fertilizers), transports (32%) and electricity consumption for the operation of the Anaerobic Digestion Plant (18%).

When considering the projection for the 2050 scenarios, a drastic reduction of emissions is observed, due to minimization of the fossil share in the generation mix – according to ***Figure 10***. There is also a reduction in the CO_2 contribution of the CO_2 input flow, assigned to the electricity demand in biogas production and purification. In the case of the most optimistic scenario "2050-3", the almost fully renewable generation (***Figure 10***) leads to less contribution from the electric input than the CO_2 supply.

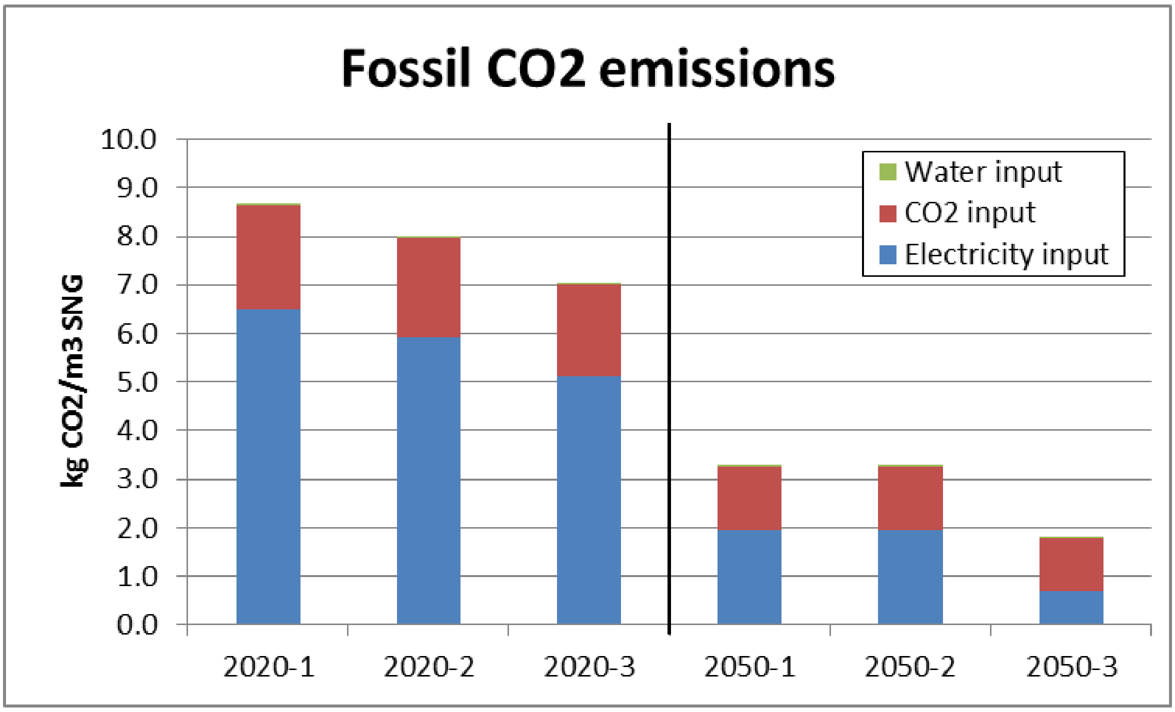

Figure 12 Fossil CO_2 emissions caused by the input flows considered (not including biogenic CO_2 or CH_4 emissions).

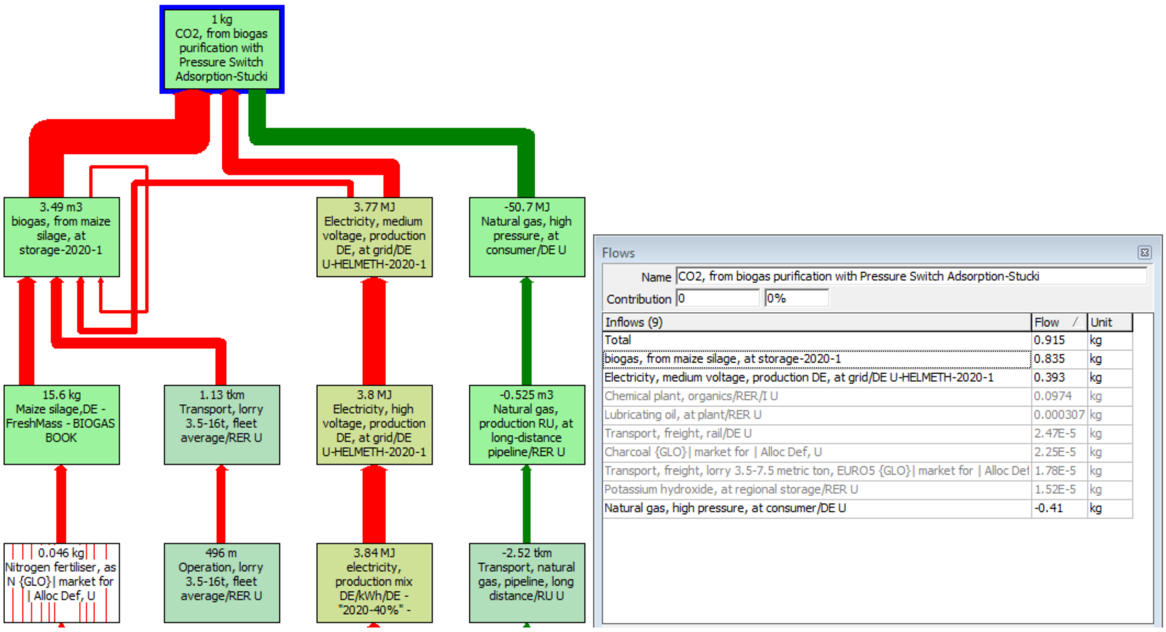

Figure 13 Contribution of upstream processes to the fossil CO_2 emissions of the CO_2 input for the HELMETH concept system operation.

5.2. Primary Energy Demand (PED)

Primary energy consumption refers to the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or

transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy is distinguished in non-renewable (fossil and nuclear) and renewable (wind, solar, biomass, etc.). The PED index refers to the Primary Energy Demand in order to accomplish an energy conversion activity or process. The calculation factors used for the present analysis are presented in the Annex.

Considering the generation scenarios of VDE-ETG (VDE-ETG, 2012), the results presented in ***Figures 14 and 15*** have been acquired. Figure 13 focuses on the case for year 2020. The biomass feedstock input to the biogas plant is responsible for the large share of biomass PED, while at the same time a comparable amount of fossil PED is displaced from the production of bio-CH_4. The electricity input demands 86.8 MJ-eq/m^3 of SNG and small amounts of renewable PED. The conversion efficiencies regarding generation from fossil PED and solar/wind PED contribute to the difference between the respective results.

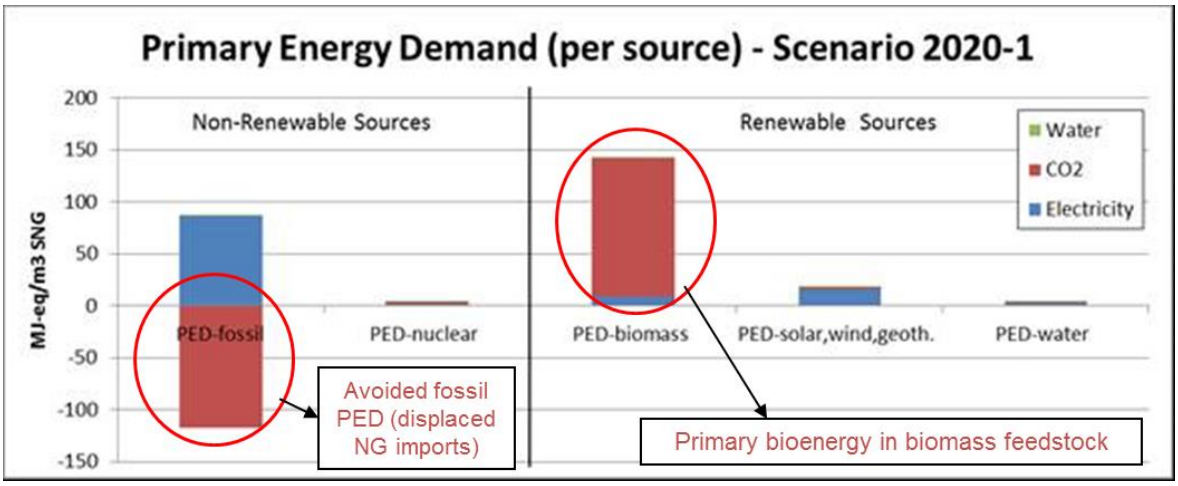

Figure 14 PED for generation Scenario 2020-1 per energy source.

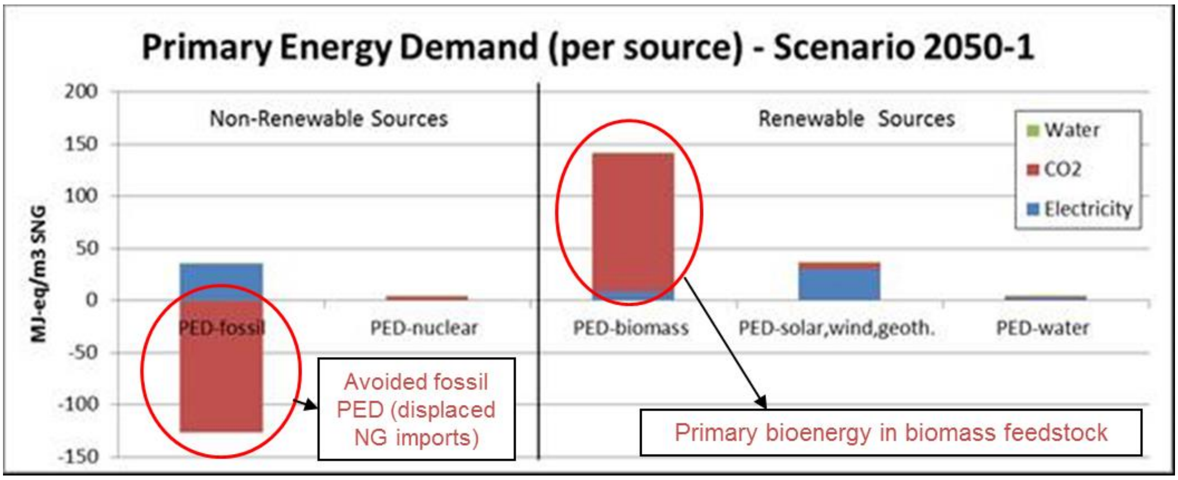

Figure 15 PED for generation Scenario 2050-1 per energy source.

The increased share of generation from renewables is reflected in the results for 2050 (***Figure 15***). While no significant changes are observed for PED-nuclear, PED-biomass and PED-water indexes,

there is a clear trade-off between the PED-fossil (-60%) and PED-solar,wind,geoth. (doubled) between 2020 and 2050. As regards the CO_2 supply side, it is slightly affected through the electric consumption in the anaerobic digester and the purification stage.

The shift towards renewable PED is also shown in ***Figure 16***, where the renewable and non-renewable sources are summed up. Assuming a biomethane plant as the "CO_2 supplier" proves to be an environmentally "niche" case, since it boosts the renewable part of the PED, while featuring a "fossil PED sink effect", through avoiding the extraction, refining and transportation of Natural Gas displaced by bio-CH_4.

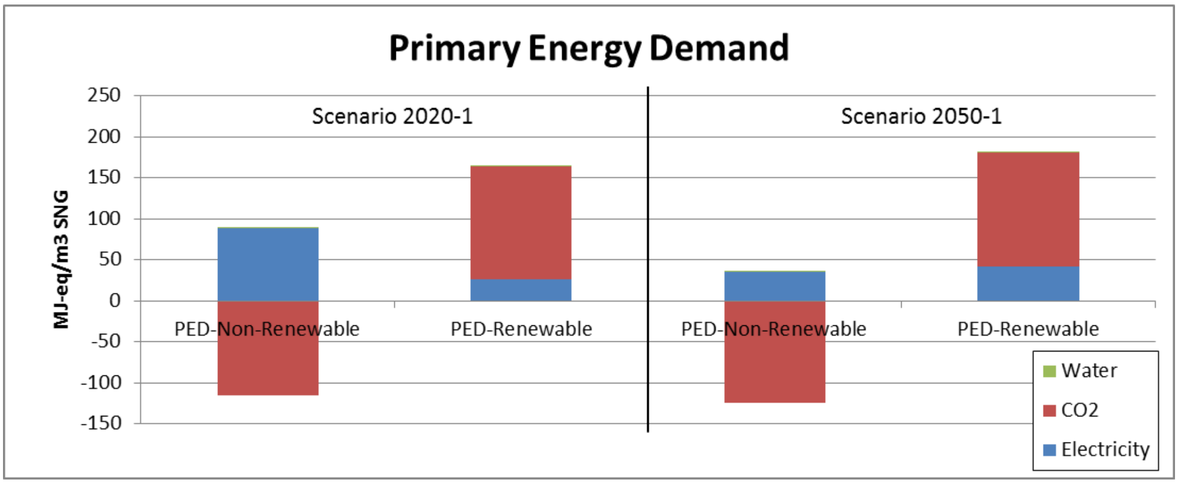

Figure 16 Renewable and non-Renewable PED of 1 m^3 SNG.

The results for all generation scenarios considered are presented in ***Figures 17 and 18*** for non-renewable and renewable PED, respectively. In brief, for the cases of year 2020, the production of 1 m^3 of SNG requires roughly 165 MJ-eq of renewable PED and displaces 25-30 MJ-eq of fossil PED. When considering the studies for 2050, the renewable PED rises at 180-195 MJ-eq/m3 SNG, with a negative fossil PED from -90 to -118 MJ-eq/m3 SNG.

Figure 17 shows that more fossil PED is avoided than consumed, leading to a negative value of the corresponding index. This is explained by the fossil PED avoided due to the production of bio-CH_4 from the biogas facility (which is considered to displace natural gas imports from Russia to Germany). The "non-RE PED sink effect" is increased in the 2050 scenarios, due to less fossil fuel combustion share in the generation mix. The corresponding non-RE PED of extracting, producing and transporting 1 m^3 of natural gas from Russia to Germany is estimated at 50 MJ-eq/m3 NG (assuming 6000 km of pipeline).

On the other hand, the biomass feed assigned to the CO_2 supply for the methanation stage is responsible for the large amount of renewable PED (***Figure 18***). The corresponding value of renewable PED of delivering 1 m^3 from Russia to Germany is near zero.

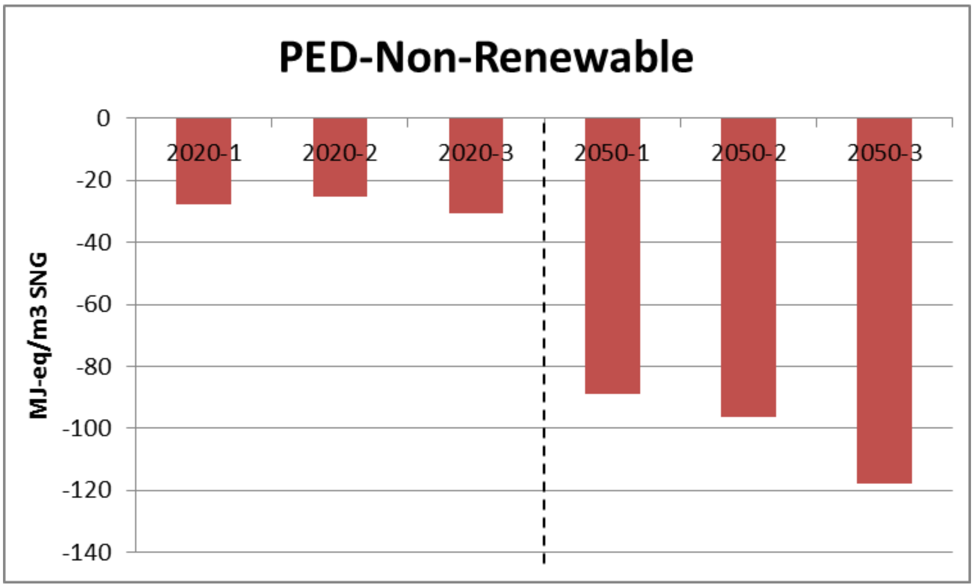

Figure 17 Non-renewable PED of the HELMETH concept system for all electricity generation scenarios considered.

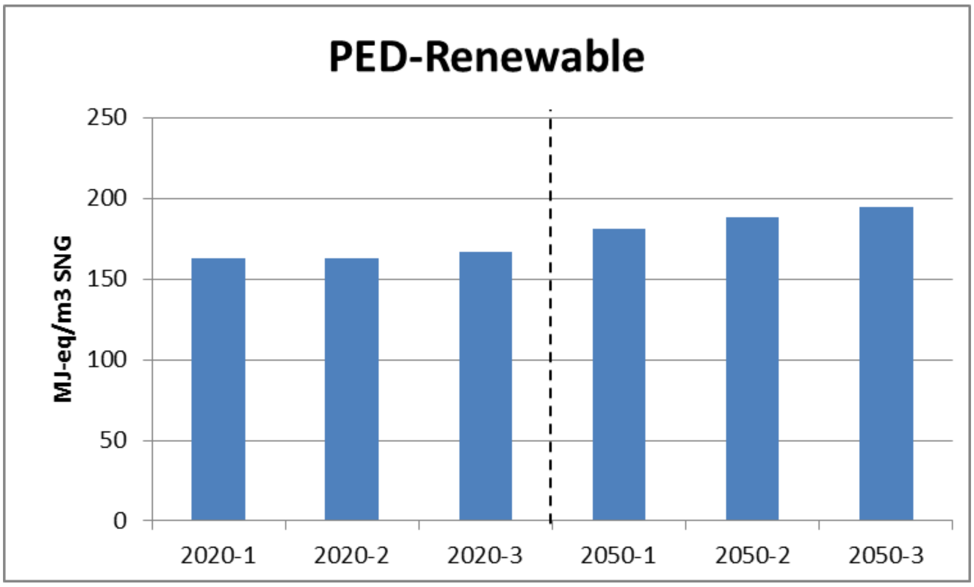

Figure 18 Renewable PED of the HELMETH concept system for all electricity generation scenarios considered.

6. Conclusion

The present analysis investigates the environmental and energetic impacts of the HELMETH concept system, in terms of CO_2 emissions from fossil fuel sources and the Primary Energy Demand for the production of 1 m^3 of Synthetic Natural Gas. Concerning the calculation of the upstream processes, efforts focused on acquiring reliable data on biogas production from maize silage, the corresponding purification stage and utilizing well-accepted studies concerning the development of the German electricity generation system in the following decades.

Provided that there will be no emissions expected from the operation stage, the environmental impacts are located in the upstream processes of supplying the input flows: electricity, CO_2 and water. In the "base case" formulated for the present analysis, the contribution of water supply proved insignificant. On the contrary, the electric generation mix is decisive towards minimizing the indirect impact and PED of the HELMETH concept system.

Assuming a strong trend towards renewable generation and the utilization of CO_2 output of a biomethane plant shows two environmental advantages: (a) the potential of a "fossil PED sink effect", since more fossil PED is avoided than consumed and (b) an output flow of SNG made by biogenic carbon, thus providing no fossil CO_2 emissions in the next stages of utilizing (burning) the SNG (not shown in the present analysis).

The results of the present deliverable can only be considered as preliminary. Due to the early stage of the HELMETH work plan, there were no experimental data available, in order to have a representative overview of the material/energy balance. Therefore, the HELMETH system operation was based on the preliminary balance presented in the Description of Work. Existing open issues (such as pressurization of CO_2 from bio-CH_4 output to the pressure requested by the HELMETH system, potential utilization of the produced O_2) and planned forthcoming steps (incorporation of the impact caused by the manufacturing and assembly of the system, comparison to benchmark electricity storage systems, investigation of alternative CO_2 sources) are to be addressed in the following stages of WP5.

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Table of Figures

List of Tables

Annexes (optional)

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Maize silage,DE - FreshMass - BIOGAS BOOK	1.0	kg	Mass	100 %	Compost	Agricultu...\Transformation	

(Insert line here)

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Carbon dioxide, in air	in air	0.4573508842	kg	Lognormal	1.2038			(2,1,4,1,1,na) Modelled,see chapter 'CO2 binding' in ""01_crop production_direct field emissions and natural resources_v1.0.pdf"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Biomass, feedstock	in ground	1.0615	kWh	Undefined				5.8 kWh Biogas/m3 NTP (Normal Temp. Press.) ; (0.34 m3/kg DryMass ; 65% moisture --> 0.119 m3/kg FreshMass BIOGAS BOOK) --> 0.69 kWh Biogas/kgFM --> 65% energetic eff. Biomass - to - Biogas (g5_04_09_1a.pdf pg. 33)

(Insert line here)

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Pesticide, unspecified {GLO}| market for | Alloc Def, U	7.384E-5	kg	Lognormal	1.497			biogas book, pg383
Potassium chloride, as K2O {GLO}| market for | Alloc Def, U	0.0044937	kg	Lognormal	1.2038			biogas book, pg383
Maize seed, Swiss integrated production, for sowing {GLO}| market for | Alloc Def, U	0.00043933	kg	Lognormal	1.2038			(2,1,4,1,1,na) See chapter 'Yields and Inputs of Arable Crop Production' in ""01_crop production - yields & inputs CH & Europe_v1.0.pdf"", section ""AGRICULTURAL PRODUCTION IN SWITZERLAND"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Def, U	0.0016878	kg	Lognormal	1.2038			biogas book, pg383
Nitrogen fertiliser, as N {GLO}| market for | Alloc Def, U	0.0029536	kg	Lognormal	1.2038			biogas book, pg383
Diesel, at regional storage/RER U	0.001738	kg	Undefined				

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Ammonia	low. pop.	0.000393711	kg	Lognormal	1.3146			(2,2,4,1,1,na) Modelled with the 'AGRAMMON model' described in ""01_crop production_direct field emissions and natural resources_v1.0.pdf"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Dinitrogen monoxide	low. pop.	5.34E-5	kg	Lognormal	1.4821			(2,2,4,1,1,na) Modelled, see chapter 'Emissions of N2O to the air' in ""01_crop production_direct field emissions and natural resources_v1.0.pdf"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Carbon dioxide, fossil	low. pop.	0.00022454	kg	Lognormal	1.2051			(2,2,4,1,1,na) Modelled, see chapter 'Release of fossil CO2 after urea applications' in ""01_crop production_assessment methods of direct field emissions_v1.0.pdf"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Nitrogen oxides	low. pop.	1.1214E-5	kg	Lognormal	1.4821			(2,2,4,1,1,na) Modelled, see chapter 'Emissions of NOx to the air' in ""01_crop production_direct field emissions and natural resources_v1.0.pdf"" - pdf-document on the dedicated talk page of ecoinvent (www.ecoinvent.org/documentation)
Water/m3		0.00241313852041653	m3	Lognormal	1.5548			(2,2,4,1,1,na) Calculated value based on literature values and expert opinion. See comments in the parametres' comment field.

Figure 19 Datasheet for the production of 1 kg of Maize Silage

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
biogas, from maize silage, at storage-2020-1	1	Nm3	Volume	100 %		Fuels\Biofuels\Biogas	

(Insert line here)

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Maize silage,DE - FreshMass - BIOGAS BOOK	4.4538	kg	Undefined				0.34 m3CH4/kg DryMass --> 0.119 m3 CH4/kg FreshMass ---> 0.2245 m3 Biogas/kgFM --> 4.4538 FM/m3 Biogas. Biogas book
Anaerobic digestion plant covered, agriculture/CH/I U	3.56E-8	p	Undefined				
Electricity, medium voltage, production DE, at grid/DE U-HELMETH-2020-1	8.27E-2	kWh	Undefined				
biogas, from maize silage, at storage-2020-1	0.07184	Nm3	Undefined				Ecoinvent: 1.2 MJ of Heat --> 1.5 MJ of biogas (80% combustion eff.) --> (5.8 kwh/m3 or 20.88 MJ/m3) --> 0.07184 m3 biogas
Transport, lorry 3.5-16t, fleet average/RER U	3.2E-1	tkm	Undefined				
application, digestate, from maize silage	5.23E0	kg	Undefined				
Anaerobic digestion plant, agriculture/CH/I U	6.06E-8	p	Undefined				

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Ammonia		2.79E-4	kg	Undefined				
Carbon dioxide, biogenic		1.64E-2	kg	Undefined				
Methane, biogenic		1.13E-2	kg	Undefined				
Hydrogen sulfide		1.26E-3	kg	Undefined				
Dinitrogen monoxide		3.38E-4	kg	Undefined				
Heat, waste		1.5E0	MJ	Undefined				

(Insert line here)

Figure 20 Datasheet for the production of 1 m^3 of biogas

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
CO2, from biogas purification with Pressure Switch Adsorption-Stucki	1	kg	Mass	100 %	not defined	Fuels\Biofuels\Biogas	As for 1 Nm3 of biogas. originalvalue of CO2: .469 for 1 m3 bioCH4 (stucki pg.83)

(Insert line here)

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Natural gas, high pressure, at consumer/DE U	52.72	MJ	Undefined				with 39MJ/m3. normalized for 53% Ch4 content in maize biogas instead for 64% in Stucki. CH4/CO2-stucki=0.64/0.36=1.778. CH4/CO2_maize=0.53/0.47=1.1277. 1.1277/1.778=0.634. Initial value of 83.156MJ*.634=52.72MJ

(Insert line here)

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
biogas, from maize silage, at storage-2020-1	3.241	Nm3	Undefined				
Electricity, medium voltage, production DE, at grid/DE U-HELMETH-2020-1	0.7569	kWh	Undefined				original value: 0.355 referring to 0.469 kg CO2. 0.355/0.469=0.7569 kWh for 1 kg CO2
Charcoal {GLO}| market for | Alloc Def, U	4.435E-4	kg	Undefined				original value: 2.08E-4. see comment above
Lubricating oil, at plant/RER U	3.198E-4	kg	Undefined				original value: 1.5E-4. see comment above
Potassium hydroxide, at regional storage/RER U	8.486E-6	kg	Undefined				original value: 3.98E-6. see comment above
Chemical plant, organics/RER/I U	8.529E-10	p	Undefined				original value: 4E-10. see comment above
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}| market for | Alloc Def, U	3.8593E-5	tkm	Undefined				original value: 1.81E-5. see comment above
Transport, freight, rail/DE U	4.6269E-4	tkm	Undefined				original value: 2.17E-4. see comment above

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Methane, biogenic		3.838E-2	kg	Undefined				
Hydrogen sulfide		4.925E-6	kg	Undefined				
Heat, waste		2.729	MJ	Undefined				
Sulfur dioxide		14.072E-6	kg	Undefined				

(Insert line here)

Figure 21 Datasheet for the production of 1 kg of CO_2 from biogas purification

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Water, deionised, at plant/CH U-HELMETH	1	kg	Mass	100 %	not defined	Water\Industry water	SWITZERLAND

(Insert line here)

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Tap water, at user/RER U	1.11000000000000010	kg	Lognormal	1.09			(nA,nA,nA,nA,nA,nA); CV calculated from range of the reported values
Hydrochloric acid, 30% in H2O, at plant/RER U	0.00024	kg	Lognormal	2.04			(nA,nA,nA,nA,nA,nA); CV calculated from range of resin and raw water
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	0.00012	kg	Lognormal	2.02			(nA,nA,nA,nA,nA,nA); CV calculated from range of resin and raw water
Electricity, medium voltage, production DE, at grid/DE U-HELMETH-2020-1	0.00045	kWh	Lognormal	1.85			(nA,nA,nA,nA,nA,nA); CV calculated from range of the reported values
Water treatment plant, deionisation/CH/I U	0.00000000009	p	Lognormal	3.18			(4,5,1,2,3,5); Estimated with weak data on plant operation
Transport, freight, rail/RER U	0.000624	tkm	Lognormal	2.09			(4,5,nA,nA,nA,nA); Estimated with standard distances
Transport, lorry 20-28t, fleet average/CH U	0.000052	tkm	Lognormal	2.09			(4,5,nA,nA,nA,nA); Estimated with standard distances

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Heat, waste	high. pop.	0.00162	MJ	Lognormal	1.85			(nA,nA,nA,nA,nA,nA); Calculated from electricity demand
Carbon dioxide, biogenic	high. pop.	0.00023	kg	Lognormal	2.04			(nA,nA,nA,nA,nA,nA); Calculated from data of chemical demand

(Insert line here)

Figure 22 Datasheet for the production of 1 kg of deionised water.

		VDE-ETG, Energiespeicher fur die Energiewende. 2012		Prognos, EWI, GWS. Entwicklung der Energiemärkte Energiereferenzprognose. 2014		OEKO Ins., FhG-ISI. Klimaschutzszenario 2050. 2014	
	Scenario in LCA datasheet	2020-1	2050-1	2020-2	2050-2	2020-3	2050-3
	Scenario in corresponding report	"2020-40%"	"2050-80%"	"2020-Target"	"2050-Target"	"2020-ClimaProtection90"	"2050-ClimaProtection90"
Primary Energy Source	**Relevant process in Ecoinvent database**	**Electricity Generation Shares**					
Hard coal	Electricity, hard coal, at power plant/DE U	11.11%	2.13%	8.09%	1.36%	9.40%	0.00%
Brown coal	Electricity, lignite, at power plant/DE U	22.22%	0.00%	26.44%	4.54%	18.16%	0.39%
NG	Electricity, natural gas, at power plant/DE U	22.22%	19.15%	9.71%	10.20%	12.18%	0.39%
Hydro	Electricity, hydropower, at power plant/DE U	4.44%	4.26%	3.42%	4.31%	5.98%	7.24%
Nuclear	Electricity, nuclear, at power plant/DE U	0.00%	0.00%	11.33%	0.00%	11.75%	0.00%
Solar	Electricity, production mix photovoltaic, at plant/DE U	11.79%	23.38%	10.25%	17.01%	9.62%	22.31%
Wind	Electricity, at wind power plant/RER U	19.32%	38.33%	20.87%	48.52%	24.36%	63.41%
Biomass (Biogas)	Electricity, at cogen with biogas engine, agr. covered, alloc. exergy/Germany 2013	6.38%	6.11%	6.97%	9.77%	2.99%	2.15%
Biomass (Solid biofuels)	Electricity, at cogen 6400kWth, wood, emission control, allocation exergy/CH U	2.51%	2.40%	2.74%	3.84%	5.56%	4.11%
Geothermal	Electricity, high voltage {DE}| electricity production, geothermal | Alloc Def, U	0.00%	4.26%	0.00%	0.00%	0.00%	0.00%

Table 1 Electricity generation shares for the Scenarios examined.

Non renewable, fossil	MJ-Eq		
(unspecified)	Oil, crude, 38400 MJ per m^3, in ground	38400	MJ-Eq / m^3
(unspecified)	Gas, natural, in ground	40.3	MJ-Eq / m^3
(unspecified)	Gas, off-gas, oil production, in ground	39.8	MJ-Eq / m^3
(unspecified)	Gas, mine, off-gas, process, coal mining/ m^3	39.8	MJ-Eq / m^3
(unspecified)	Gas, natural, 36.6 MJ per m^3, in ground	36.6	MJ-Eq / m^3
(unspecified)	Gas, petroleum, 35 MJ per m^3, in ground	35	MJ-Eq / m^3
(unspecified)	Gas, natural, feedstock, 35 MJ per m^3, in ground	35	MJ-Eq / m^3
(unspecified)	Gas, natural, 35 MJ per m^3, in ground	35	MJ-Eq / m^3
(unspecified)	Gas, mine, off-gas, process, coal mining/kg	49.8	MJ-Eq / kg
(unspecified)	Gas, natural, feedstock, 46.8 MJ per kg, in ground	46.8	MJ-Eq / kg
(unspecified)	Gas, natural, 46.8 MJ per kg, in ground	46.8	MJ-Eq / kg
(unspecified)	Oil, crude, in ground	45.8	MJ-Eq / kg
(unspecified)	Oil, crude, 42.7 MJ per kg, in ground	42.7	MJ-Eq / kg
(unspecified)	Oil, crude, 42.6 MJ per kg, in ground	42.6	MJ-Eq / kg
(unspecified)	Oil, crude, feedstock, 42 MJ per kg, in ground	42	MJ-Eq / kg
(unspecified)	Oil, crude, 42 MJ per kg, in ground	42	MJ-Eq / kg
(unspecified)	Oil, crude, feedstock, 41 MJ per kg, in ground	41	MJ-Eq / kg
(unspecified)	Oil, crude, 41 MJ per kg, in ground	41	MJ-Eq / kg
(unspecified)	Methane	35.9	MJ-Eq / kg
(unspecified)	Gas, natural, 30.3 MJ per kg, in ground	30.3	MJ-Eq / kg
(unspecified)	Coal, 29.3 MJ per kg, in ground	29.3	MJ-Eq / kg
(unspecified)	Coal, feedstock, 26.4 MJ per kg, in ground	26.4	MJ-Eq / kg
(unspecified)	Coal, 26.4 MJ per kg, in ground	26.4	MJ-Eq / kg

(unspecified)	Coal, hard, unspecified, in ground	19.1	MJ-Eq / kg
(unspecified)	Coal, 18 MJ per kg, in ground	18	MJ-Eq / kg
(unspecified)	Peat, in ground	13	MJ-Eq / kg
(unspecified)	Coal, brown, 10 MJ per kg, in ground	10	MJ-Eq / kg
(unspecified)	Coal, brown, in ground	9.9	MJ-Eq / kg
(unspecified)	Coal, brown, 8 MJ per kg, in ground	8	MJ-Eq / kg
(unspecified)	Energy, from sulfur	1	MJ-Eq / MJ
(unspecified)	Energy, from peat	1	MJ-Eq / MJ
(unspecified)	Energy, from oil	1	MJ-Eq / MJ
(unspecified)	Energy, from gas, natural	1	MJ-Eq / MJ
(unspecified)	Energy, from coal, brown	1	MJ-Eq / MJ
(unspecified)	Energy, from coal	1	MJ-Eq / MJ
Non-renewable, nuclear	MJ-Eq		
(unspecified)	Uranium, 2291 GJ per kg, in ground	2291000	MJ-Eq / kg
(unspecified)	Uranium, in ground	560000	MJ-Eq / kg
(unspecified)	Uranium, 560 GJ per kg, in ground	560000	MJ-Eq / kg
(unspecified)	Uranium, 451 GJ per kg, in ground	451000	MJ-Eq / kg
(unspecified)	Uranium ore, 1.11 GJ per kg, in ground	1110	MJ-Eq / kg
(unspecified)	Energy, from uranium	1	MJ-Eq / MJ
Renewable, biomass	MJ-Eq		
(unspecified)	Energy, gross calorific value, in biomass	1	MJ-Eq / MJ
(unspecified)	Energy, from wood	1	MJ-Eq / MJ
(unspecified)	Energy, from biomass	1	MJ-Eq / MJ
(unspecified)	Biomass, feedstock	1	MJ-Eq / MJ
Renewable, wind, solar, geothe	MJ-Eq		
(unspecified)	Energy, solar, converted	1	MJ-Eq / MJ
(unspecified)	Energy, kinetic (in wind), converted	1	MJ-Eq / MJ
(unspecified)	Energy, geothermal	1	MJ-Eq / MJ

Renewable, water	MJ-Eq		
(unspecified)	Water, barrage	0.01	MJ-Eq / kg
(unspecified)	Energy, potential (in hydropower reservoir), converted	1	MJ-Eq / MJ
(unspecified)	Energy, from hydro power	1	MJ-Eq / MJ

Table 2 Factors for calculating the Primary Energy Demand (PED) index. Method to calculate Cumulative Energy Demand (CED), based on the method published by ecoinvent version 1.01 and expanded by PRé Consultants for raw materials available in the SimaPro 6 database.Source: Frischknecht R., Jungbluth N., et.al. (2003). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000, Swiss Centre for LCI. Duebendorf, CH, www.ecoinvent.ch