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Glossary

Abbreviation / acronym	Description
P2G	Power-to-Gas
SNG	Substitute/Synthetic Natural Gas
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
CO_2-eq	Carbon dioxide equivalent
H2	Hydrogen
CO	Carbon monoxide
CH4	Methane
H2O	Water
PED	Primary Energy Demand
NTP	Normal Temperature and Pressure
GWP	Global Warming Potential
DAC	Direct Air Capture
PSA	Pressure Switch Adsorption
AS	Amine Scrubbing
MEA	Monoethanolamine

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 5.2 has the goal to to identify the ecological performance of power-to-gas technology in terms of the innovative HELMETH concept and the main parameters influencing Global Warming Potential (GWP). The results of Substitute Natural Gas (SNG) derived from Power-to-Gas were compared to natural gas extraction and transportation to Central Europe. Although ISO 14040 standards on LCA only cover assessments of environmental impacts of a product, the methodology can also be applied to processes. The software SimaPro (PRé Consultants BV, Version 8) (see https://www.pre-sustainability.com) was utilized for modeling Power-to-Gas pathways and calculating environmental impacts. The specific objectives are:

- To evaluate and quantify the combined influence of the type of electricity source (carbon load of electric input), the PtG efficiency and the type of CO2 source in the relevant environmental impacts.
- To identify the limits of “carbon-negative” and “better-than-NG” SNG production in terms of GWP.

The major findings regarding the GWP of HELMETH SNG production were the following:

- Carbon negative operation is achieved by non-fossil CO_2 sources and an electric feed GWP of below 140-150 g CO_2-eq/kWh. Therefore, carbon negative operation is feasible, even with current or near future grid power input. In other words, a full renewable input is not a necessity.
- Lower GWP than extracting and transporting fossil NG is achieved by:
  - biogenic/atmospheric sources and electric carbon load of below 180-190 gr CO_2-eq/kWh and
  - fossil CO_2 source (however carrying only the corresponding compression impact) and a near fully renewable electric input (below 40 gr CO_2-eq/kWh).
- Existing PtG concepts powered by LT-electrolyzers feature higher requirements in terms of «clean» electric feed in order to achieve «Carbon negative» or «Better-than-NG» environmental performance. Relevant calculations show a requirement of 30% lower GWP of the electric feed, in order to reach the GWP values of PtG operation with HT-electrolysers.

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 (PtG) 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).

The present analysis investigates the environmental impacts of the HELMETH concept system, in terms of Global Warming Potential for the production of 1 MJ of Synthetic Natural Gas. The results of CH_4 derived from Power-to-Gas were compared to natural gas extraction and transportation to Central Europe. Three key parameters have been identified that primarily influence the results:

- Electricity input. Relevant scenarios developed: Electricity generation from wind power, German electricity mix of 2020 and corresponding projection for 2050;
- CO2 separation impact. Corresponding scenarios: CO_2 as waste product from biogenic sources (biogas and biomethane plants), from ambient air (DAC) or specific separation from the flue gases of coal/natural gas fired power plants and of industrial sources (cement/steel production and refinery)
- Electrolyzer (PtG) efficiency. The influence of the improved PtG efficiency provided by the High Temperature electrolysis/Heat Integration concept of HELMETH has been quantified, compared to standard PtG efficiencies from Low Temperature electrolysis technologies.

2.2. Goal & Scope

The goal of this LCA was to identify the ecological performance of power-to-gas technology in terms of the innovative HELMETH concept and the main parameters influencing GWP. The results of CH_4 derived from Power-to-Gas were compared to natural gas extraction and transportation to Central Europe. Although ISO 14040 standards on LCA only cover assessments of environmental impacts of a product, the methodology can also be applied to processes. The software SimaPro (PRé Consultants BV, Version 8) (see https://www.pre-sustainability.com) was utilized for modeling Power-to-gas pathways and calculating environmental impacts. The specific objectives are:

- To establish a baseline of the overall resource use, energy consumption and environmental loadings of a “base case” scenario

- To evaluate and quantify the combined influence of the type of electricity source (carbon load of electric input), the PtG efficiency and the type of CO2 source in the relevant environmental impacts.
- To identify the limits of “carbon-negative” and “better-than-NG” SNG production in terms of GWP.

2.3. Functional unit and geographical scope

The function of power-to-gas technology is, on the one hand, storing electricity, and on the other hand, the production of an energy carrier that can be applied for heat generation, electricity generation, or as fuel for transport applications. The energy content of SNG was selected as a functional unit, due to the primary application for final energy provision. All results of the LCA are therefore related to 1 MJ of CH4, based on higher heating value (HHV). The HHV of SNG is 39 MJ per m3 (NTP).

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.

2.4. System boundaries

The definition of system boundaries determines input and output flows considered, as well as the process steps of the evaluated system. The life cycle usually begins with extraction of raw materials and energy carriers and ends with waste generation, energy recovery, or disposal. According to ISO 14044 (2006) regulations on system boundaries, it is not permissible to cut short process models if this results in fundamental limitations for LCA conclusions. Since the present LCA excludes the process step of product utilization, it can be specified to be a cradle-to-gate LCA. Fig. 1 shows the system boundaries of the LCA conducted, with a focus on the production of SNG under the HELMETH concept.

The production of SNG includes process steps such as water electrolysis, methanation, CO2 separation/compression and electricity production. This LCA includes electricity inputs from wind power and the German electricity mix projections for 2020 (40% renewable contribution) and 2050 (80% renewable contribution). The CO2 required for the methanation is distinguished into fossil and biogenic/atmospheric sources. Fossil CO2 can be extracted from various point sources, such as flue gas from power plants, industrial process in steel and cement production. On the other hand, biogenic sources would include various fermentation processes, while the option of ambient air separation (Direct Air Capture – DAC) has been also considered.

The CO2 separation from flue gas of a coal and natural gas combustion via amine scrubbing was selected within this assessment. Due to the high partial pressure of CO2 in the biogas stream, the separation method of pressure switch adsorption (PSA) was additionally considered. For the case of utilizing the waste CO2 from a biomethane facility the separation is assumed to be already performed. The reference process for SNG derived from Power-to-Gas technology was natural gas extraction and pipeline transportation to Central Europe.

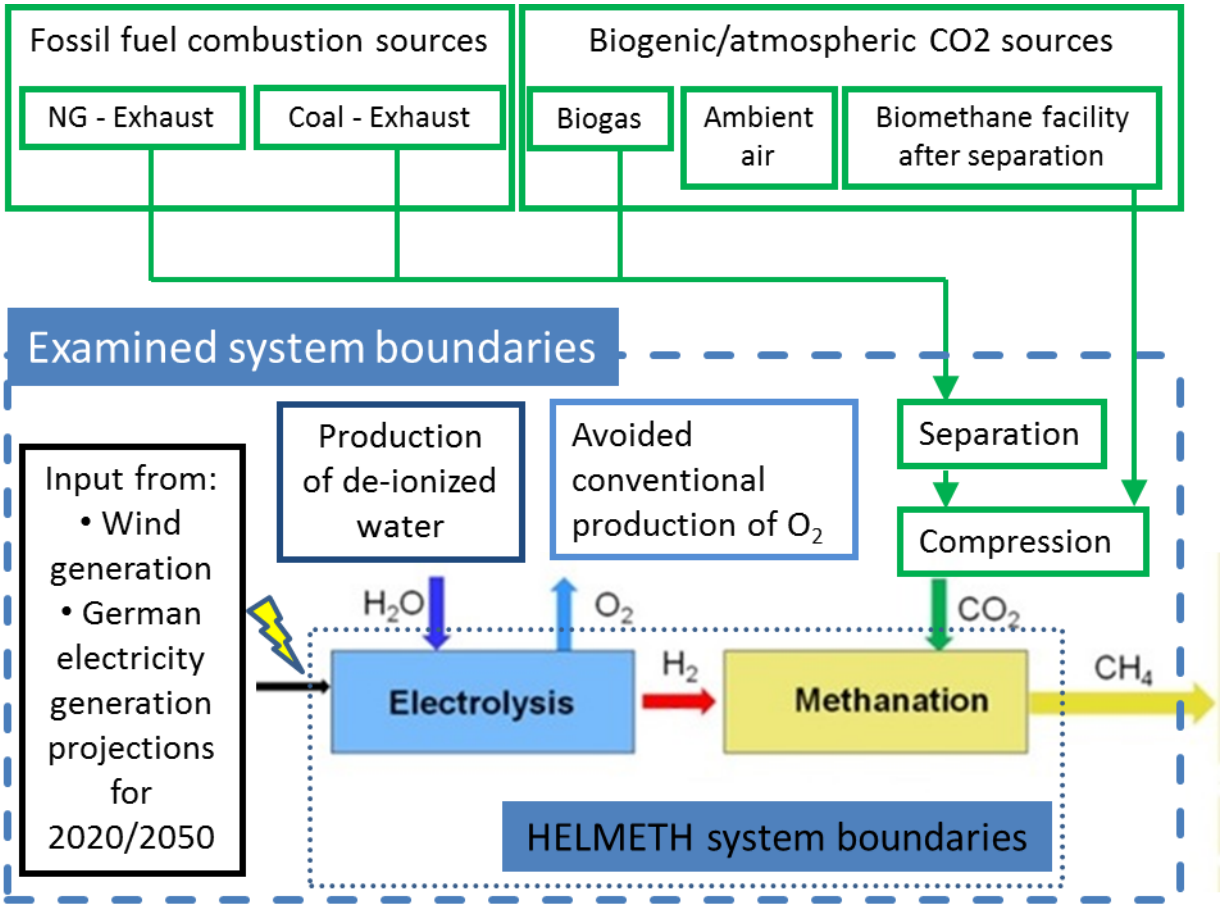

Figure 1 Boundaries of the life cycle modelling for the HELMETH system

2.5. Impact Categories

This LCA evaluates the environmental impacts of Power-to-Gas in the impact category of climate change. The impact category climate change with the indicator GWP in kg CO2 equivalents was calculated using the CML 2001 (Guinee et al. 2001) method developed by the Institute of Environmental Sciences at the University of Leiden in the Netherlands (De Bruijn et al. 2002), which implements the ISO 14040 standard. For calculation of CO2 equivalents of different air emissions, characterization factors were applied as per the Intergovernmental Panel on Climate Change (IPCC), considering a time horizon of 100 years (IPCC, 2007).

2.6. Sensitivity Analysis

Three key parameters have been identified by both the present analysis and by Reiter and Lindorfer (2015) that primarily influence the results. These are the origin of electricity input, the effort for CO2 separation, and the efficiency of the electrolyzer. The following scenarios were developed to account for these uncertainties in the sensitivity analysis:

(a) Electricity generation from wind power, German electricity mix of 2020 and corresponding projection for 2050;

(b) CO2 as waste product from biogenic sources (biogas and biomethane plants), from ambient air (DAC) or specific separation from the flue gases of coal/natural gas fired power plants and of industrial sources (cement/steel production and refinery); and

(c) Impact of operation mode on the efficiency of the PtG concept, providing the influence of the improved PtG efficiency provided by the High Temperature electrolysis/Heat Integration concept of HELMETH, compared to standard PtG efficiencies from Low Temperature electrolysis technologies.

3. Life Cycle Inventories: Summary

The inputs and outputs of different Power-to-Gas process steps, as well as of reference processes, were described with data from literature and manufacturers. The material and energy balance is required as an input for modeling using the LCA software SimaPro. This LCA considered the resources required for SNG production and the related supply chain. The mass/energy balance presented in ***Figure 2*** is based on relevant deliverables and working documents.

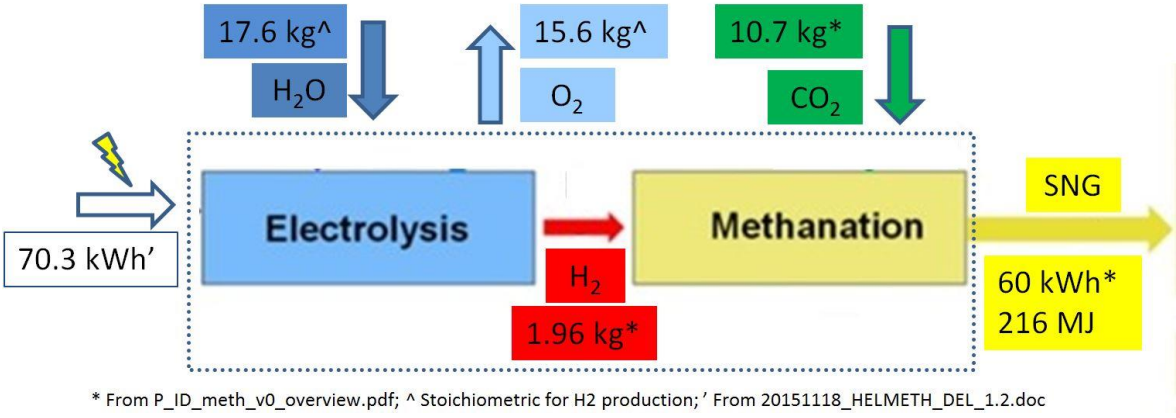

Figure 2 Mass/energy balance for hourly operation

As regards by-products, full recirculation of water condensates has been assumed, meaning that the water flow herewith considered (fig. 2) accounts only for the respective H_2 production under stoichiometry. The utilization of the O_2-rich flow from the electrolyzer may not be currently performed, however it will be considered in the present study, since it has been already proposed (Goetz et al., 2016) or examined in economic terms (Gahleitner and Lindorfer, 2013).

Subchapters 3.1-3.3 describe the resources and electricity needed for the process, while subchapter 3.4 describes the by-product of the process.

3.1. 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. For this reason and due to being less optimistic, it has been selected as the base for all calculations that follow.

Two electricity generation scenarios have been formulated (fig.3 - 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 reaches 80%.

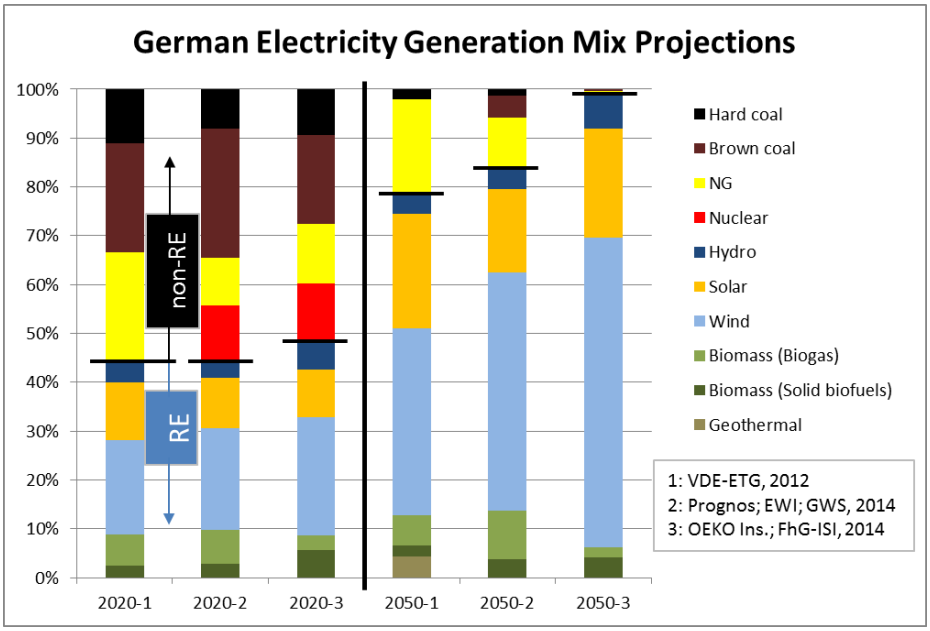

Figure 3 German Electricity Generation Mix Projections.

3.2. CO_2 input

Carbon dioxide is a by-product of many industrial processes and is emitted in large amounts during fuel combustion in power plants. To limit global warming, the reduction of CO_2 emissions is required, which can be realized in the hierarchy of prevention, storage, and recycling. However, as current CO_2 mitigation measures are not sufficient to effectively limit the increase of CO_2 in the atmosphere, another approach is to capture it from point sources. Once captured, CO_2 can be stored in underground reservoirs such as saline aquifers, exploited oil and gas fields or deposits under the seabed. However, so-called carbon capture and storage faces problems including leakage, risks to the environment, considerable costs, energy requirements (Reiter and Lindorfer, 2015) and negative public acceptance.

Another possibility is to utilize the captured CO_2 for the synthesis of polymers, fuels and chemicals. The methanation process in the Power-to-Gas system is an example of a carbon capture and utilization (CCU) technology. The required CO_2 can basically originate from either fossil or renewable point sources (IPCC, 2001; IPCC Working Group, 2005; IEA GHG, 2002a). Fossil CO_2 sources include off-gases from power plants or industrial processes such as lime or cement

production. Renewable sources comprise biotechnological anaerobic digestion and other fermentation processes that release CO_2. Furthermore, CO_2 can be absorbed from ambient air.

Figure 4 (Reiter and Lindorfer, 2015) provides an overview of potential CO_2 sources and the related concentrations. The majority of CO_2 sources have concentrations less than 15 vol. %. However, some sources also indicate possible CO_2 concentrations above 95 vol. % and are therefore promising for the early implementation of capture techniques. The concentration and purity of CO_2 in the exhaust gas significantly influences the efficiency of the subsequent separation processes. In general, the technical implementation of CO_2 capture becomes easier and more economical as the CO_2 partial pressure in the exhaust gas increases (Metz et. al, 2005). A qualitative overview of different separation technologies is provided in Fig. 5 (Reiter and Lindorfer, 2015).

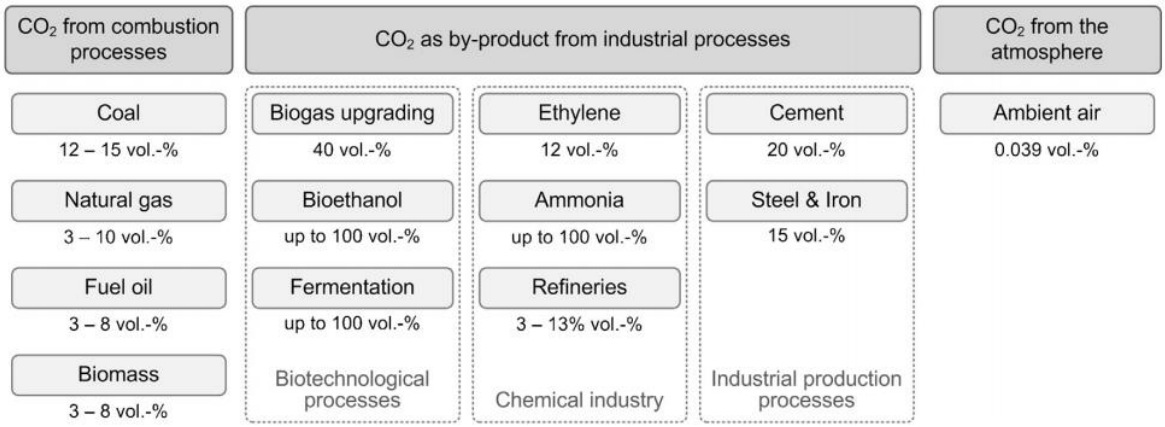

Figure 4 Overview of potential CO_2 sources and related concentrations (Reiter and Lindorfer, 2015; IEA GHG, 2002a)

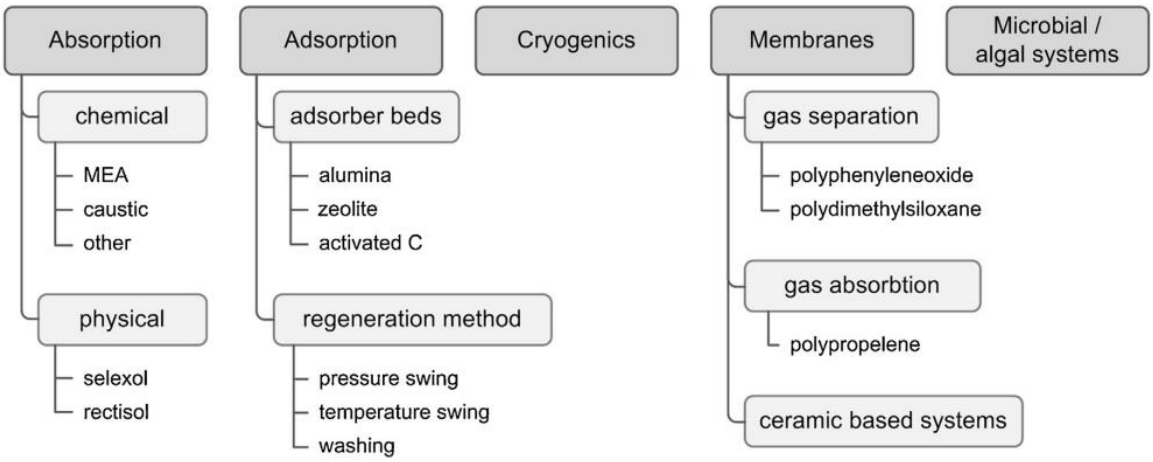

Figure 5 Schematic overview of CO_2 separation technologies (Reiter and Lindorfer, 2015; Metz et al., 2005)

Chemical and physical absorption are well-established methods for CO_2 separation in industrial processes and power plants and can be relatively easily integrated (Sreenivasulua et. al, 2015). Chemical absorption typically employs amine-based solvents such as monoethanolamine (MEA), and physical absorption employs organic solvents like selexol or rectisol. However, the

regeneration of the solvents requires a relatively high thermal energy input. Adsorption processes exhibit very high selectivity but have not yet been utilized in commercial applications. The specific energy requirement demand of adsorption processes is also significant, but the further development of the adsorbents promises a huge potential for energy savings (Sreenivasulua et. al, 2015). Cryogenic condensation is a well-known and state-of-the-art process in breweries and bioethanol production. The process operates at high pressure and low temperature and has a lower energy requirement than existing absorption and adsorption processes (Sreenivasulua et. al, 2015). In streams with high CO_2 content, the separation efficiency is high and the remaining CO_2 has a high purity. However, cryogenic technologies for CO_2 separation are sensitive to moisture and have very high specific costs (Sreenivasulua et. al, 2015). Membrane technology is especially suited for post-combustion processes and air separation units but is still in the development stage. Due to the modular design of the technology, CO_2 separation with membranes can be utilized for smaller applications. The energy requirement is low, but the membranes used are sensitive to several gas components. Critical parameters for the various membranes are selectivity and permeability (Sreenivasulua et. al, 2015).

In addition to the CO_2 separation technologies presented in fig. 4, there are two more processes for CO_2 capture from combustion processes that do not require a further separation step. In the first, the oxyfuel process, the fuel is not burned in air, as in conventional combustion, but in pure oxygen and thus without the presence of nitrogen. The oxygen is generated using the energy intensive cryogenic air separation method, which is a state-of-the art technology. In the second, the chemical looping process, an absorbent (e.g. metal oxide) reacts with CO_2 produced in situ during oxidation in a fluidized bed reactor to form carbonate. The metal oxide is then regenerated from the carbonate in a second reactor by elimination of the pure CO_2 with air (Reiter and Lindorfer, 2015). By avoiding direct contact between the fuel and air, the resulting combustion flue gas consists primarily of CO_2 and water.

Among the potential CO_2 sources and the possible separation techniques, the cases presented in figures 6 and 8 were considered. The following paragraphs present the relevant data and assumptions for the biogenic/atmospheric and fossil CO_2 sources examined, respectively.

3.2.1 Biogenic/atmospheric CO_2 sources examined

Biogenic CO_2 sources include biogas production and upgrading, bioethanol production and other fermentation processes in alcohol, vinegar, or acetone production. The present study will focus on biogas from anaerobic digestion as a representative and widespread (both in current and future terms) biogenic source (Graf and Bajohr, 2013 - pg. 319; DVGW, 2013). Biogas contains a large proportion of CH_4, approximately 40 vol. % of CO_2 and some other trace components. After a cleaning step for removal of trace components, the CO_2 is separated from the biogas to obtain biomethane of appropriate quality for injection into the gas distribution grid. Applied separation technologies for this step are physical or chemical absorption, pressure swing adsorption and membrane separation (Ryckebosch et al., 2011). For the present study the two most common

techniques are considered (Stucki et al., 2011), the Amine Scrubbing (AS) with MEA and Pressure Swing Adsorption (PSA). As considers the atmospheric capture or DAC (Direct Air Capture), the relevant process by Climeworks (www.climeworks.com) was considered.

Every combination of source and separation method considered demands electricity and in some cases also heat (fig. 6). The emissions related to the delivery of the power (and possibly heat) required for separating (which is not necessary in the Biomethane case) and compressing the CO_2 flow up to the HELMETH pressure requirements will quantify the GWP of the CO_2 input flow, however not exclusively. Biogenic sources capture the respective CO_2 feed from ambient air, either in a straightforward way (DAC), or indirectly during biomass cultivation (biogas, biomethane). The total GWP load of the CO_2 input flow for methanization will therefore be the difference of the GWP created by delivering the power/heat for separation/compression of the respective flow source minus the GWP displaced during CO_2 capturing.

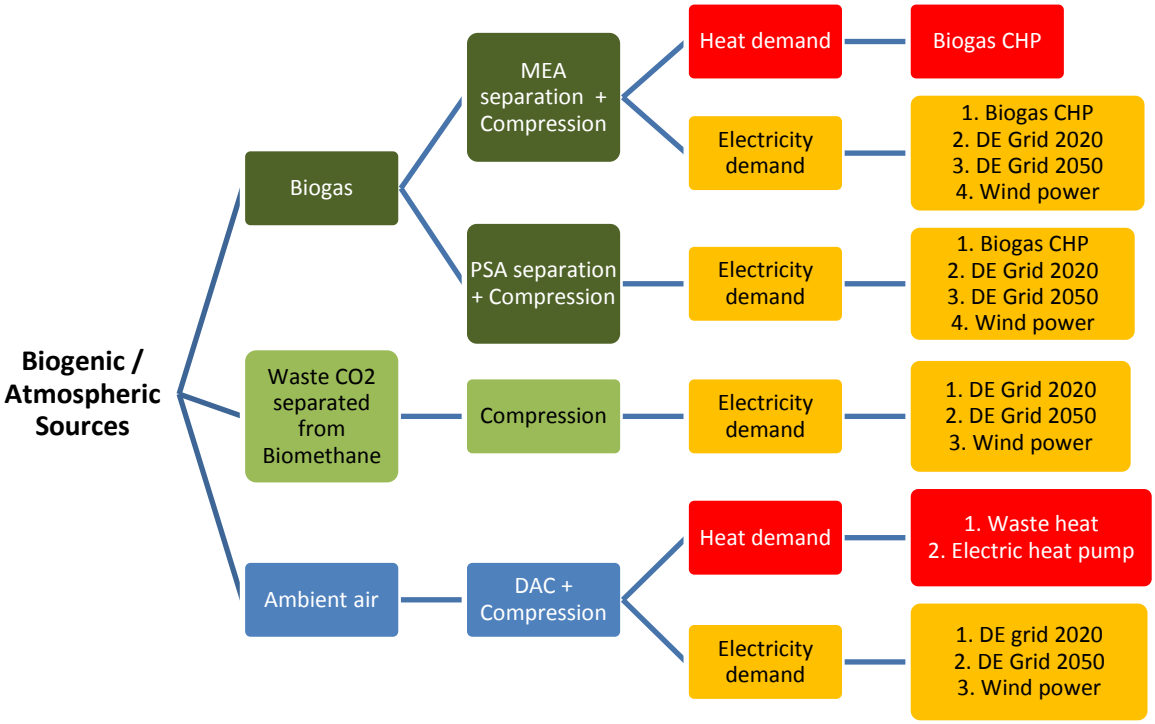

Figure 6 Biogenic/atmospheric CO_2 source cases examined (total: 17)

The separation/compression power demand is covered in four ways: Two German generation mix projections for 2020 and 2050 (cases 2020-1 and 2050-1 of fig. 3), a Wind power case and an assumption of own consumption of the CHP engine attached to the Biogas plant. The latter assumption is not applicable for the biomethane (since there is injection to the NG grid) and the DAC (no proximity to any local power generation is assumed). On the other hand, the heat demand is also provided by CHP in the biogas case. For DAC, two extreme assumptions took place: the respective low-grade heat demand is taken (with zero carbon emissions associated) from a waste (or solar) heat flow or (with maximum carbon emissions) from a typical electric driven heat pump

(COP=4.5). The second assumption would refer to fully electric DAC operation, independent from local heat supply.

The values of the corresponding specific heat and electricity demands are presented in fig. 7. A biogas composition 47% vol. CO2 and 53% vol. CH4 (typical for anaerobic digestion of maize silage) was assumed, leading to 0.62 kg of CO_2 capture for 1 m3 of biogas (biogas density: 1.13 kg/m3). A higher and lower value is shown for the Biogas-MEA case, due to a difference in the data acquired from relevant literature.

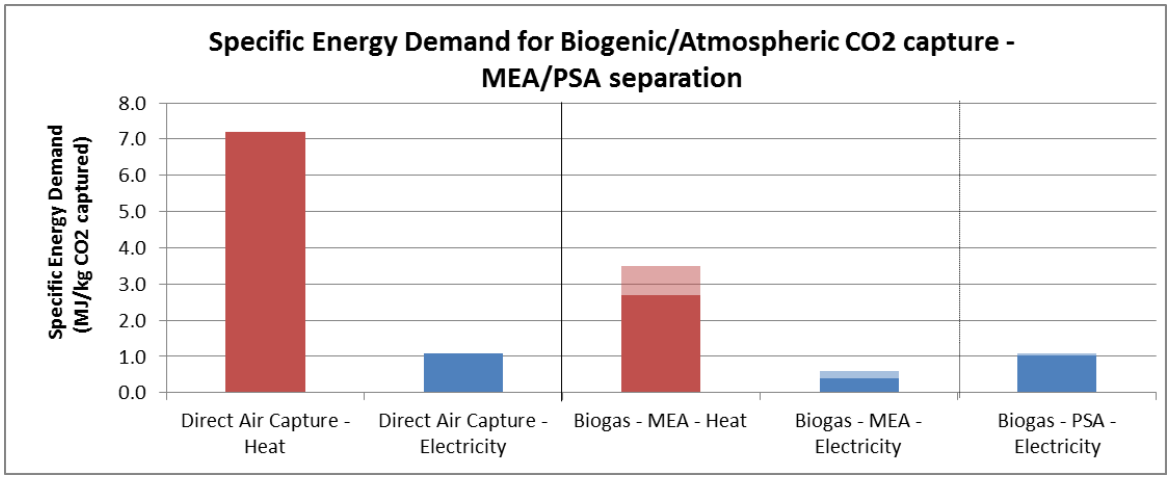

Figure 7 Specific Energy Demand for Biogenic/Atmospheric CO_2 capture. Sources: Climeworks (2017); Graf and Bajohr (2013), Stucki et al. (2011).

As regards the compression stage, the electricity demand is calculated at 0.1 kWh/kg CO2 (assuming adiabatic compression and 80% compressor efficiency), which is in agreement with the corresponding value in deliverable D1.1. The power consumption of compression is the only energy assumed spent in the case of utilizing the waste CO_2 from a biomethane facility (fig. 6).

3.2.2 Fossil CO_2 sources examined

Combustion processes in power plants emit huge amounts of CO_2 and represent a potential source for CO_2 that could be utilized in power-to-gas plants. Apart from fossil fuels such as coal, natural gas, and fuel oil, biomass combustion also causes CO_2 emissions. Basically, there are three possible methods of CO_2 capture from combustion processes (Metz et al., 2005):

- post-combustion (CO_2 separation from the flue gas of a power plant),
- pre-combustion (CO_2 separation before fuel combustion), or the
- oxyfuel process.

All of the technologies presented in fig. 5 are suitable for post-combustion CO_2 separation. The most frequently employed methods are chemical absorption (with MEA), physical absorption, or pressure swing adsorption. Post-combustion processes typically have a CO_2 capture efficiency of 85–90% (Rubin et al., 2012). In pre-combustion processes, the fuel initially reacts with water vapor to form H_2 and carbon monoxide (CO) in a first gasification step. The CO_2 is then separated from the exhaust gas using one of the technologies listed in fig. 5. The high CO_2 content in the shifted

syngas enables a comparatively efficient CO_2 capture via physical absorption, reaching capture efficiencies of up to 95% (Rubin et al., 2012). The flue gas consists primarily of CO_2 and water vapor, which can be removed with little effort by condensation after cooling. The major disadvantage of the oxyfuel process is that large quantities of pure oxygen have to be provided by extraction from air, which significantly reduces the overall efficiency (Reiter and Lindorfer, 2015). Oxyfuel combustion enables CO_2 capture efficiencies of approximately 90% (Rubin et al., 2012).

CO_2 from fossil resources is emitted in large amounts as a result of numerous processes in the chemical industry. In ammonia production plants, CO_2 is produced in the steam reforming of natural gas, a process for H_2 production (Metz et al., 2005). CO_2 could also be captured from various processes in refineries, such as steam cracking, fuel combustion in process heaters, or H_2/ethylene production. Suitable capture technologies include the post-combustion process with chemical absorption or the oxyfuel process, leading to CO_2 capture efficiencies of 59–77% and 77–84%, respectively (Kuramochi et al, 2012). The production and processing of metals is another large source of CO_2, with iron and steel production as the main emitters. Two main ironmaking processes are mostly considered (Reiter and Lindorfer, 2015), namely the blast furnace and smelting reduction processes. CO_2 is captured via chemical or physical absorption in the blast furnace process, reaching a capture efficiency of approx. 65% (Kuramochi et al., 2012). Due to the higher CO_2 concentration of 25–35 vol. % in the gas from the smelting reduction process, capture efficiencies up to 90% can be reached (Kuramochi et al., 2012). The production of mineral products such as cement, clinker and lime also causes a huge amount of CO_2 emissions. This is due to the large energy requirements of those production processes and CO_2 emissions from the chemical calcination process (approx. 60%) (Kuramochi et al., 2012). The heat required for cement production is primarily generated from coal. Kuramochi et al. (2012) state that post-combustion is the most suitable technology for carbon capture in cement production because it can be retrofitted easily. With chemical absorption, a capture efficiency of 85% can be reached. For the present study the post-combustion separation of Amine Scrubbing (AS) with MEA is considered, since being the most common technique and applicable to all cases.

In power plants, most studies focus on an overall process in which the absorption process is integrated into the power plant (Metz et al., 2005) (fig. 9). The heat requirement is at such levels that low-pressure steam, for example condensing at 0.3 MPa(g), can be used in the reboiler. The steam required for the regeneration process is then extracted from the steam cycle in the power plant. For a coal fired power station, low-pressure steam will be extracted prior to the last expansion stage of the steam turbine. For a natural gas fired combined cycle, low-pressure steam will be extracted from the last stage in the heat recovery steam generator. Some of this heat can be recovered by preheating the boiler feed water (Metz et al, 2005). For the industrial sources, the necessary heat is provided by the common fuel used on site (Reiter and Lindorfer, 2015) (fig. 8). As concerns the electric demand, for the power plants it is provided from own consumption and for the industrial sources according to the electric feed cases already described (fig. 8).

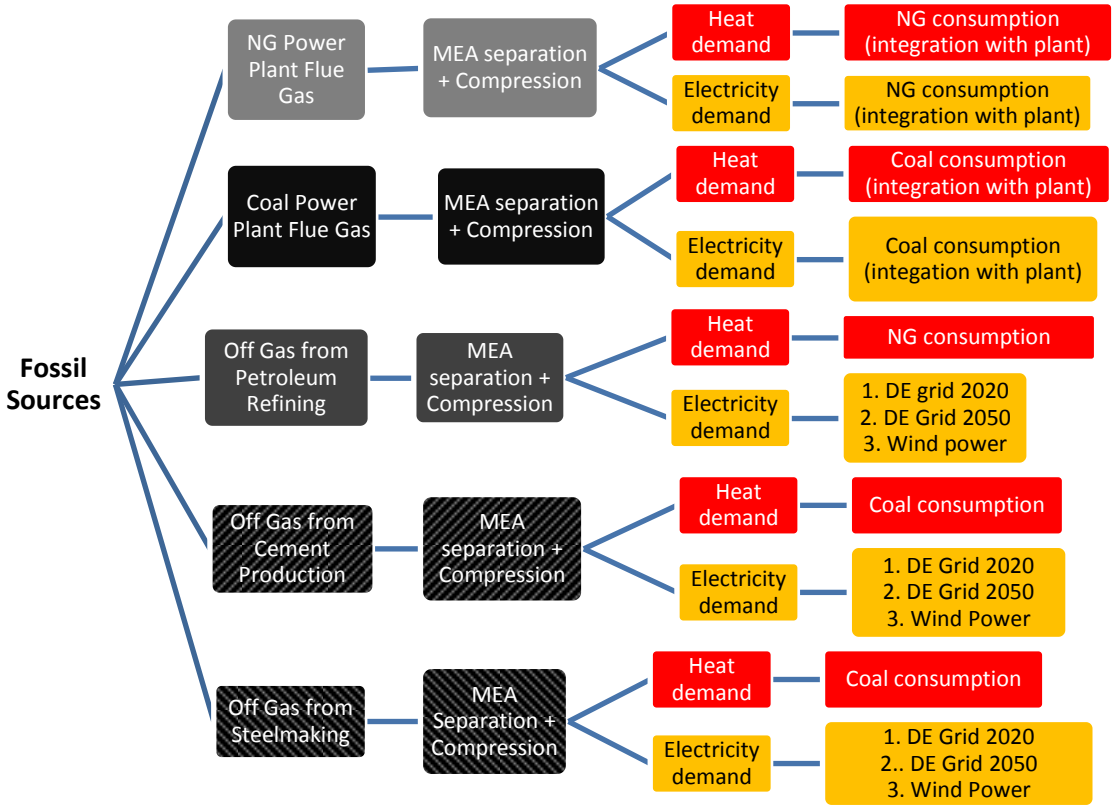

Figure 8 Fossil CO_2 source cases examined (Total 11)

The values of the corresponding specific heat and electricity demands are presented in fig. 10. For the power plants, data from Metz et al. (2005) were used, as provided in fig. 9, with the additional fuel use covering the total energy requirements for separation, since an integrated separation process is considered. Kuramochi et al., 2012 provided the data for the industrial sources. The range between a minimum and a maximum value of the corresponding energy demands reported by the literature is also presented in fig.10.

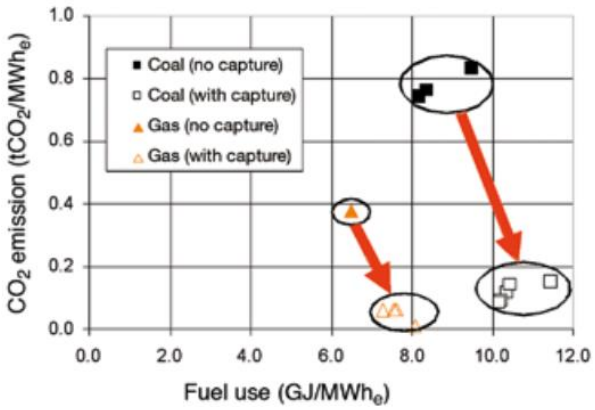

Figure 9 Fuel use for a reduction of CO_2 emissions from capture plants (data presented from design studies for power plants with and without capture). Source: Metz et al., 2005.

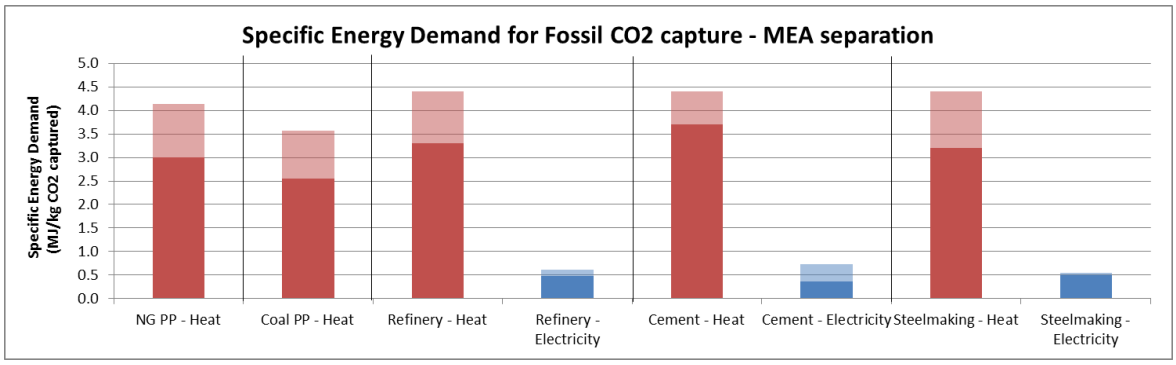

Figure 10 Specific Energy Demand for Fossil CO_2 capture. Max-min values according to the variation of reported data. Sources: Metz et al., 2015 and Kuramochi et al., 2012.

The compression is handled according to the relevant description in the previous paragraph.

3.3. Water

The power-to-gas concept includes two production steps (see fig.2): the water (steam) 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, deionized, at plant/CH U” of the Ecoinvent LCA database, modified in terms of electric input.

3.4. O_2 output

The oxygen flow from the electrolyzer can be considered as a potentially usable by-product. According to ISO 14044, “allocation should be avoided by expanding the product system to include the additional functions related to the co-products”, thus in the present study the O_2 outflow will replace the equivalent O_2 production from a reference system. In other words, the impact of producing O_2 with the reference system is considered as avoided. Provided that the vol% of O_2 in this specific flow is between 20% and 50%, the reference O_2 production system should provide the same levels of purity. From Banaszkiewicz et al. (2014), the selected reference system would be Polymer Membrane separation, providing a purity level of 40%. The corresponding specific electric demand is provided by Belaissaoui et al. (2014), with the membrane selectivity as parameter. Assuming a 40% vol. as reference purity and a common value for membrane selectivity, the value of 0.07 kWh/kg O2 will be considered as avoided electric consumption. The type of electric input avoided is modelled according to the scenarios described in the previous paragraphs.

4. Life Cycle Impact Assessment

The inventories described in Chapter 3 were used as data input to specialized LCA software (SimaPro v. 8), in order to acquire results regarding the Global Warming Potential caused by the input/output flows considered (Electricity, CO_2, O_2 and water). The GWP index includes the corresponding upstream emissions caused by the input/output 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 MJ of Synthetic Natural Gas (functional unit).

4.1. GWP of the CO_2 input

The assumptions/data presented in fig. 6 and 7 were processed in order to calculate the GWP load of the CO_2 input from non-fossil sources.

Figs. 11, 12 and 13 show the results of non-fossil sources for the three cases of electric input: DE grid 2020, DE grid 2050 and wind power, respectively. Figs. 11a, 12a and 13a present both positive impacts (due to energy demand) and negative impact (due to CO2 capture). All biogenic/atmospheric sources capture 1 kg of CO_2 (equals an avoided GWP of 1 kg of CO_2-eq) for each kg of CO_2 delivered for methanation. Figs. 11b, 12b and 13b show the corresponding balance. All three figures include the results for the cases of utilizing electricity and heat from local biogas CHP, which are not affected by the different type of electric input.

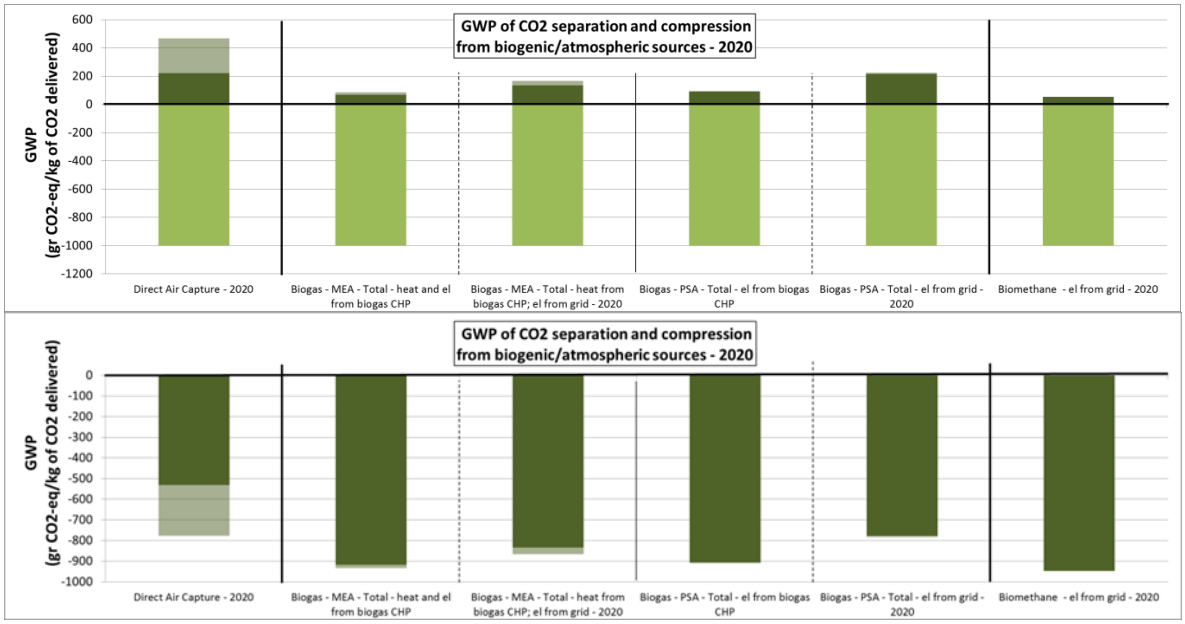

Figure 11a, b. GWP of CO_2 separation/compression from biogenic/atmospheric sources – Electric input for separation/compression: DE grid 2020.

a (top): Positive (GWP of separation/compression; max-min values according to the assumptions of §3.2.1) and negative (avoided GWP due to CO_2 capture) impacts.

b (bottom): Balance (positive minus negative GWP) of impacts. Max-min values according to the assumptions of §3.2.1

The GWP avoided during biomass growth or through DAC is considerably higher than the GWP created from the electric/thermal energy requirements for separation/compression (fig. 11). The high energy demand of DAC reduces the negative impact of CO_2 capture, especially if there is no waste heat to utilize. Best performing cases are “Biogas separation with heat/power from biogas CHP” and “Biomethane”. Electric driven separation (PSA) is not favoured by the high carbon load of the 2020 DE grid (GWP-2020: 0.567 kg CO_2-eq/kWh).

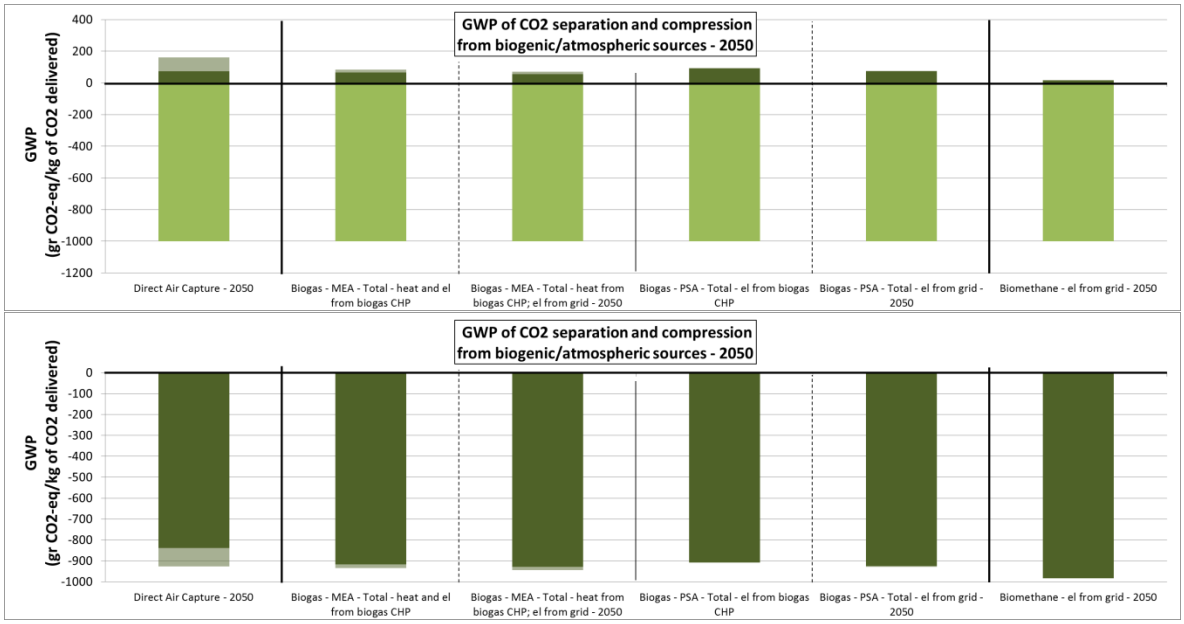

Figure 12a, b. GWP of CO_2 separation/compression from biogenic/atmospheric sources – Electric input for separation/compression: DE grid 2050.

a (top): Positive (GWP of separation/compression; max-min values according to the assumptions of §3.2.1) and negative (avoided GWP due to CO_2 capture) impacts.

b (bottom): Balance (positive minus negative GWP) of impacts. Max-min values according to the assumptions of §3.2.1

In fig. 12 the effect of the 2050 grid with 80% renewable generation contribution (corresponding GWP-2050: 0.189 kg CO_2-eq/kWh) is shown. The case of utilizing electricity from the biogas CHP is not affected. PSA separation performs more or less equally than MEA and DAC has similar GWP if zero impact heat is provided. The minimal electric demand of compression is decisive for the biomethane case to have the highest negative impact.

The electric driven separation is even more promoted if wind power input is considered (GWP of wind generation: 0.014 kg CO_2-eq/kWh) (fig. 13). There is virtually no “CO_2 penalty” for compression/separation in the corresponding cases.

Figure 13a, b. GWP of CO_2 separation/compression from biogenic/atmospheric sources – Electric input for separation/compression: Wind Power.

a (top): Positive (GWP of separation/compression; max-min values according to the assumptions of §3.2.1) and negative (avoided GWP due to CO_2 capture) impacts.

b (bottom): Balance (positive minus negative GWP) of impacts. Max-min values according to the assumptions of §3.2.1

The assumptions/data presented in fig. 8 and 10 were processed in order to calculate the GWP load of the CO_2 input from fossil sources.

Figures 14, 15 and 16 show the results of fossil sources for the three cases of electric input: DE grid 2020, DE grid 2050 and wind power, respectively. The power plant cases (NG PP – total and Coal PP – total) are not affected by the different type of electric input.

For each kg of fossil CO_2 input, a GWP between 0.3-0.4 kg CO_2-eq is calculated for NG sources (NG PP and refinery) and between 0.45-0.57 kg CO_2-eq for Coal sources. The industrial sources receive some benefit from “cleaner” electric input, however not high, due to the fact than MEA separation is heat driven.

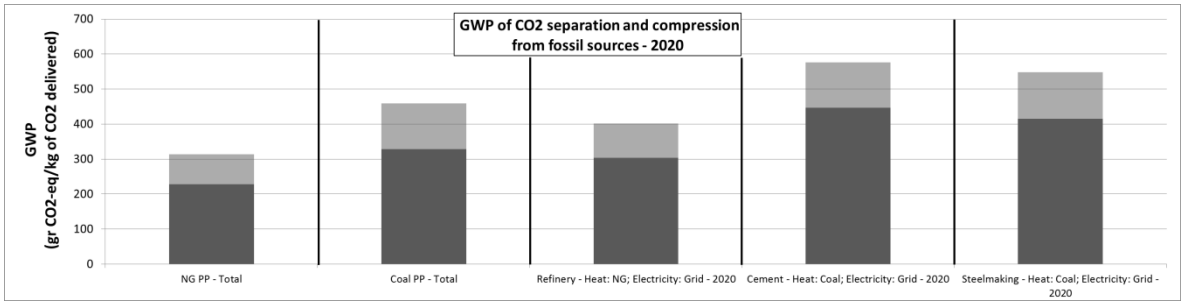

Figure 14. GWP of CO_2 separation/compression from fossil sources – Electric input for separation/compression: DE grid 2020. Max-min values according to the respective values of fig. 10.

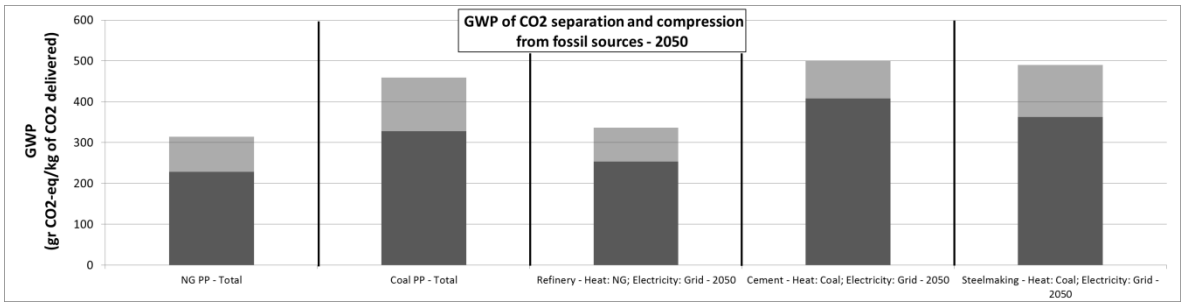

Figure 15. GWP of CO_2 separation/compression from fossil sources – Electric input for separation/compression: DE grid 2050. Max-min values according to the respective values of fig. 10.

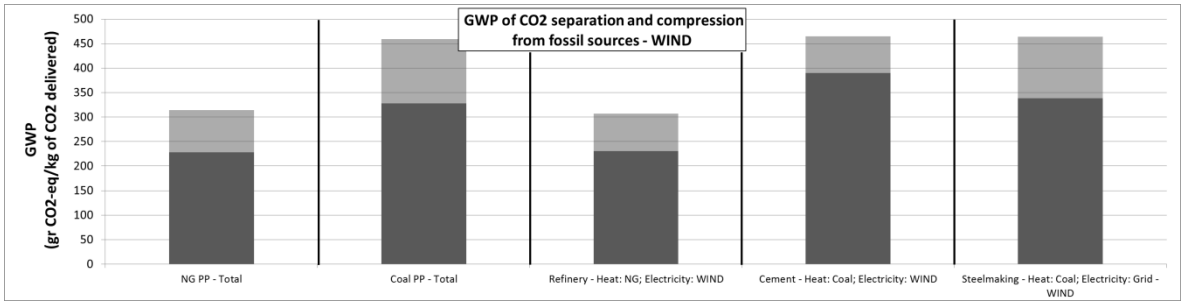

Figure 16. GWP of CO_2 separation/compression from fossil sources – Electric input for separation/compression: Wind Power. Max-min values according to the respective values of fig. 10.

4.2. GWP of the HELMETH concept system operation

By introducing the carbon load of the various cases of CO2 input and considering the mass/energy balance of fig. 2, the following results are obtained, providing the GWP of producing 1 MJ of SNG. In accordance to the previous paragraph, figures 17, 18 and 19 refer to the three electric input cases earlier described. The same electric input applies for all CO2 input cases.

The reference process for SNG production is the extraction/transportation to DE of fossil natural gas. According to the Ecoinvent LCA database, the NG grid of Germany contains imports from Russia (36%), Norway (27%) and Holland (19%), plus a national production of 18%. The calculation of the GWP for the reference case results in 12 g CO_2-eq/MJ of NG, with the Russian imports contributing almost 70% of this value (contribution of 8.34 g CO_2-eq/MJ), due to increased extraction losses and long pipeline distances. If only the Russian imports were considered, the reference GWP would be raised in the level of 20 g CO_2-eq/MJ of NG, instead of 12.

As expected, the electricity generation is responsible for the major part of the CO2 emissions on the “2020” scenario (fig. 17), due to the share of the combustion of fossil fuels. The variation of the total GWP reflects the high/low values of the results of paragraph 4.1. The inputs from non-fossil CO2 sources produces SNG with approximately 30% lower GWP. There is a small benefit from O_2 utilization and an insignificant (barely visible) contribution by the water supply flow. The high carbon load of the electric input is decisive for the large difference with the reference case.

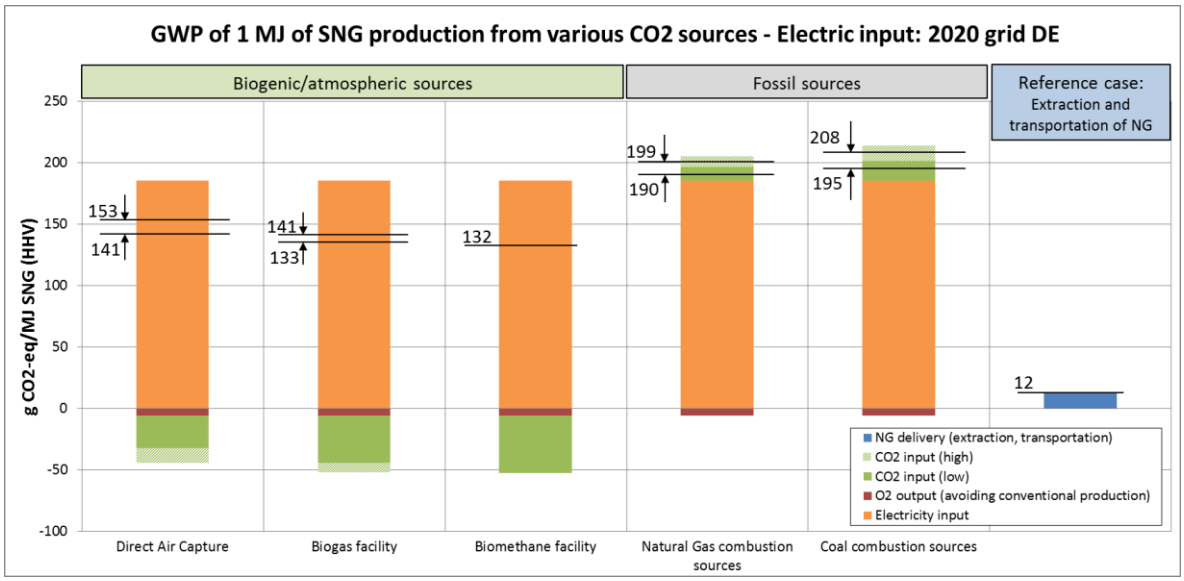

Figure 17. GWP of producing 1 MJ of SNG – All electric inputs (CO_2 separation/compression, electrolysis/PtG BoP, O_2 conventional production, water treatment): DE grid 2020.

When considering the projection for the 2050 generation scenario, a drastic reduction of GWP is observed (Fig. 18), due to reduction of the fossil share in the generation mix – according to ***Figure 3***. There is also a higher negative GWP impact of the CO_2 input flow, assigned to the "cleaner" electricity demand in separation/compression. The SNG produced from a non-fossil source has approximately 1/5 of GWP of the fossil CO_2 feed cases. The GWP of electricity input is counterbalanced to the point of almost reaching the corresponding value of the reference case.

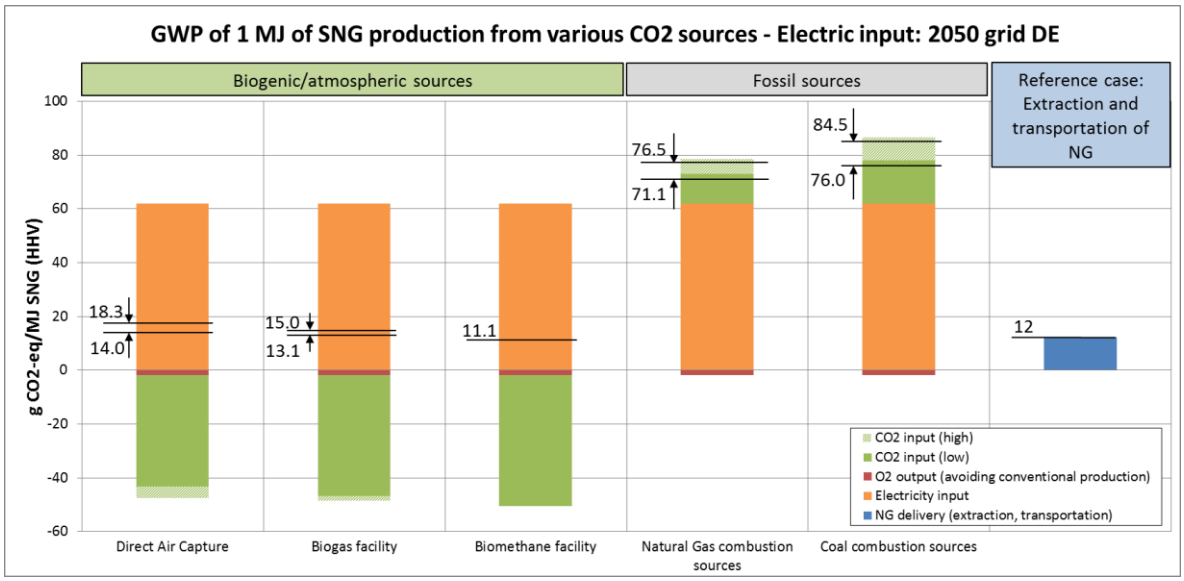

Figure 18. GWP of producing 1 MJ of SNG – All electric inputs (CO_2 separation/compression, electrolysis/PtG BoP, O_2 conventional production, water treatment): DE grid 2050.

The minimal carbon load of the wind power input and a non-fossil CO_2 source provide a "carbon-negative" PtG operation (fig. 19). For each MJ of SNG produced a GWP reduction of 40-45 gr CO_2-eq is shown. At such low carbon load condition of the electric input, the significance of the CO_2

source is more than evident. Even the fossil sources emit down to only 33% more GWP than the reference case.

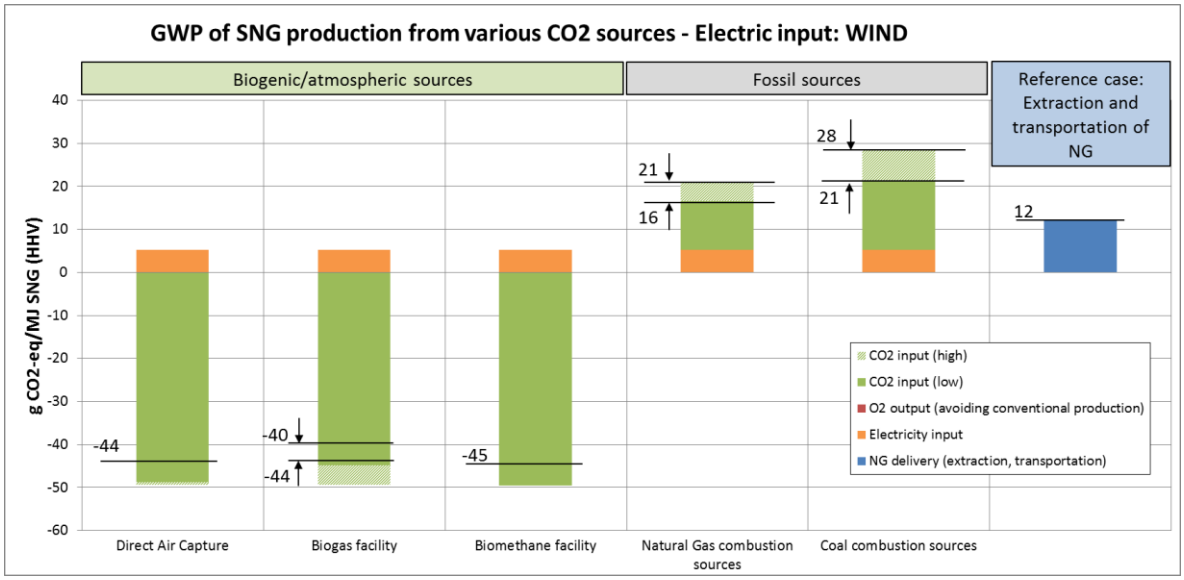

Figure 19. GWP of producing 1 MJ of SNG – All electric inputs (CO_2 separation/compression, electrolysis/PtG BoP, O_2 conventional production, water treatment): Wind Power.

In order to provide a general overview of the GWP behaviour of the HELMETH concept system operation, the results of figs. 17, 18 and 19 were interpolated in to one single contour diagram, covering a wide range of possible electric and CO_2 feeds. Fig. 20 can be characterized as the "Carbon map" of the HELMETH concept system operation (assuming 85% HHV PtG efficiency, according to deliverable 1.2).

The vertical Y-axis contains the GWP of the electricity feed for all relevant consumptions (CO_2 separation/compression, electrolysis/BoP of PtG, O_2 conventional production and treatment of water input), ranging from the top value of the German grid in 2020 (567 g CO_2-eq/kWh – scenario 2020-1 of fig.3), down to the minimum GWP of Wind power generation (14 g CO_2-eq/kWh). All possible carbon loads of the electric feed for PtG are therefore represented. On the horizontal axis is the range of carbon load for supplying 1 kg of CO_2 for methanation, set according to the results shown in figs. 11-16 and covering all sources considered.

The coloured section of the contour diagram represents the results of the GWP for producing 1 MJ of SNG. Results shown in fig. 17 would be placed on the top edge (line for electric feed GWP: 567 g CO_2/kWh) and correspondingly, fig. 18 results would be placed on the line for 189 g CO_2-eq/kWh and fig. 19 results on the bottom edge line for 14 g CO_2-eq/kWh.

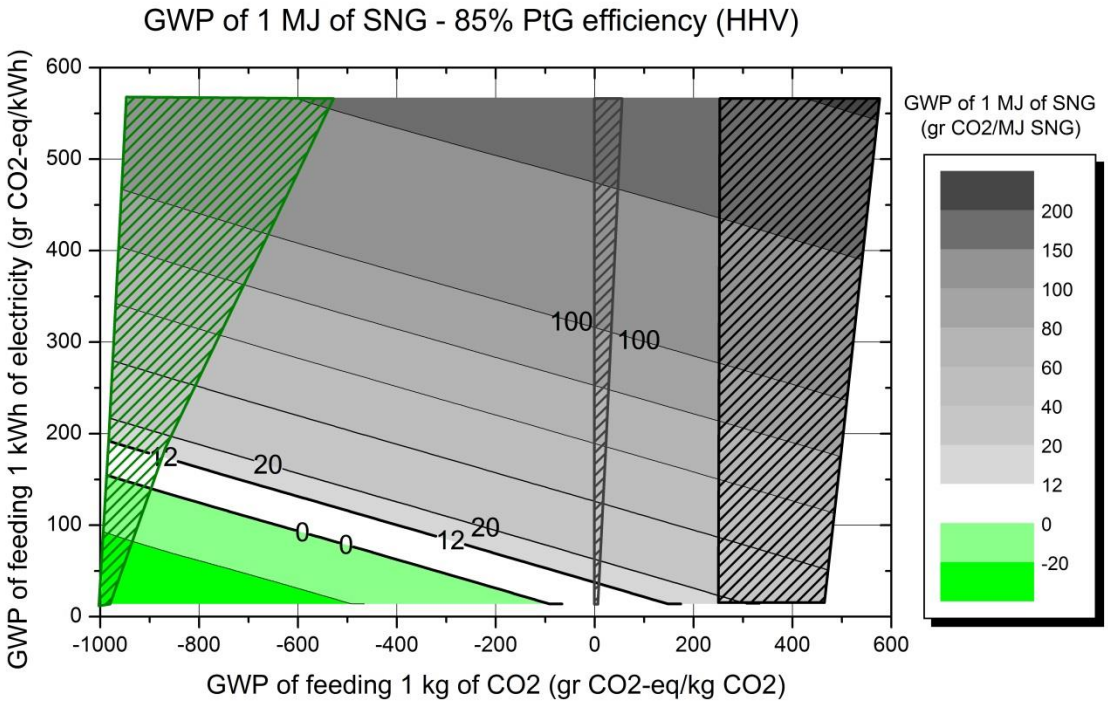

Figure 20 "Carbon map" of the HELMETH concept system operation.

Three regions are identified within the contour graph:

- "Worse than NG": GWP of producing 1 MJ of SNG > 12 g CO_2-eq.

All the grey sections represent the cases where the GWP of SNG is higher than the corresponding potential of the reference case. Light grey stands for cases which are close to the reference GWP (12 g CO_2 eq/MJ) and dark grey for higher GWP of SNG (see legend with colour palette values to the right).

- "Better than NG – Positive impact": GWP of producing 1 MJ of SNG between 0 and 12 g CO_2-eq.

The white strip represents lower GWP than the reference case, however positive.

- "Carbon negative": GWP of producing 1 MJ of SNG is below zero.

The green regions represent the cases where the avoided GWP during DAC or biomass growth is higher than the corresponding impact of power input generation and CO_2 treatment (see also fig. 19).

The three hatched areas (green, light grey and dark grey from left to right) represent (a) the non-fossil CO_2 sources, (b) fossil sources only with CO_2 compression impact and (c) fossil sources with separation and compression impact.

It is shown that carbon negative operation is achieved only by non-fossil CO_2 sources (as expected) and an electric side GWP of around 140-150 g CO_2-eq/kWh. The projections for the German grid for 2050 range between 72 and 190 g CO_2-eq/kWh, while the electric carbon load of

other European countries (France, Switzerland, Norway) falls below 70 CO_2-eq/kWh, even in current terms. Therefore, carbon negative operation is feasible, even without a full renewable electric input.

Lower GWP than extracting and transporting NG is achieved by biogenic/atmospheric sources and electric carbon load of around 180-190 gr CO_2-eq/kWh and also by a fossil CO_2 source (carrying only the corresponding compression impact) and a near fully renewable electric input (below 40 gr CO_2-eq/kWh). The latter can represent the case of a fossil power plant or an industrial source already capturing CO_2 emissions.

If the separation GWP is considered, CO_2 from a fossil source burning NG (NG plant, refinery) and electricity input from wind generation provide only ~30% more impact than the reference case (see also fig. 19).

4.3. Effect of higher PtG efficiency due to HT-electrolysis

Towards assessing the effect of higher PtG efficiencies introduced by HT-electrolyzers (core components of the HELMETH concept system) against the corresponding efficiencies of existing LT systems, the fig. 21 was calculated. A lower PtG efficiency has been assumed (61%), representative of a conventional existing system. In comparison to the assumptions behind fig. 20, only a higher electric input (according to the lower efficiency) is herewith considered.

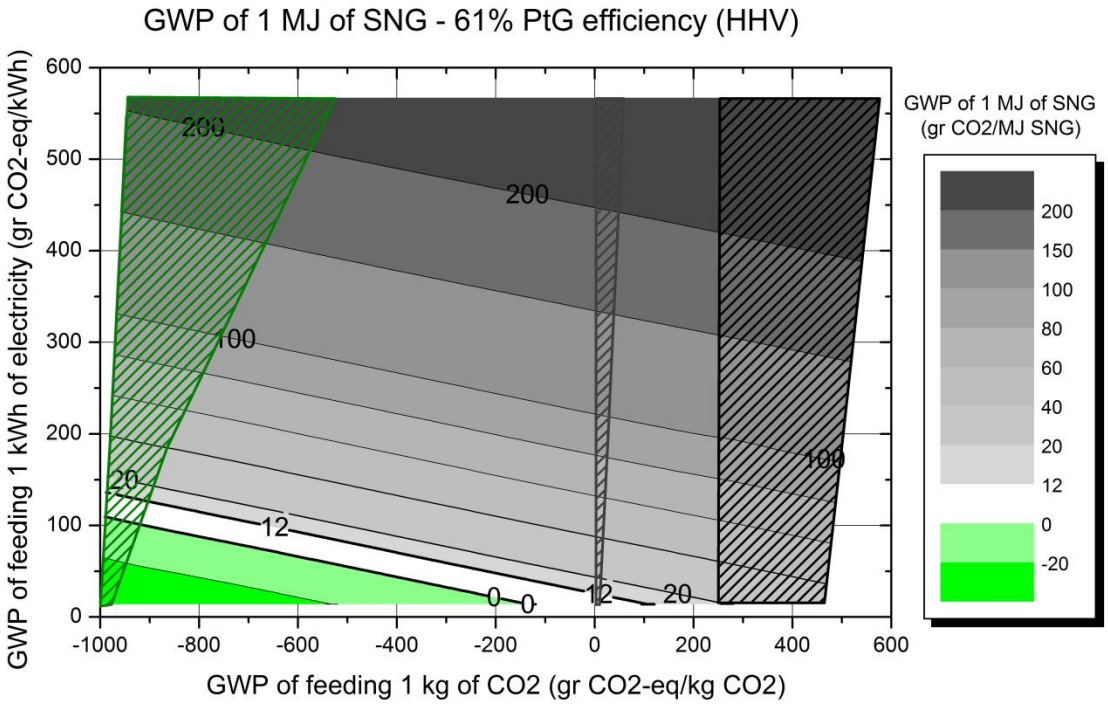

Figure 21 "Carbon map" of PtG with conventional (low temperature) electrolyzers.

The comparison between fig. 20 and fig.21 shows that a quite "cleaner" electric feed is required from LT-electrolyzers, in order to achieve "Carbon negative" and "Better than NG" operation.

Carbon negative operation is achieved at 100 gr CO2-eq/kWh, while 140 g CO2-eq/kWh are required to reach less GWP than the reference case. Figs. 22 and 23 provide a more detailed overview on these differences. Higher differences in favour of the HT electrolyzers are observed at higher electric carbon loads.

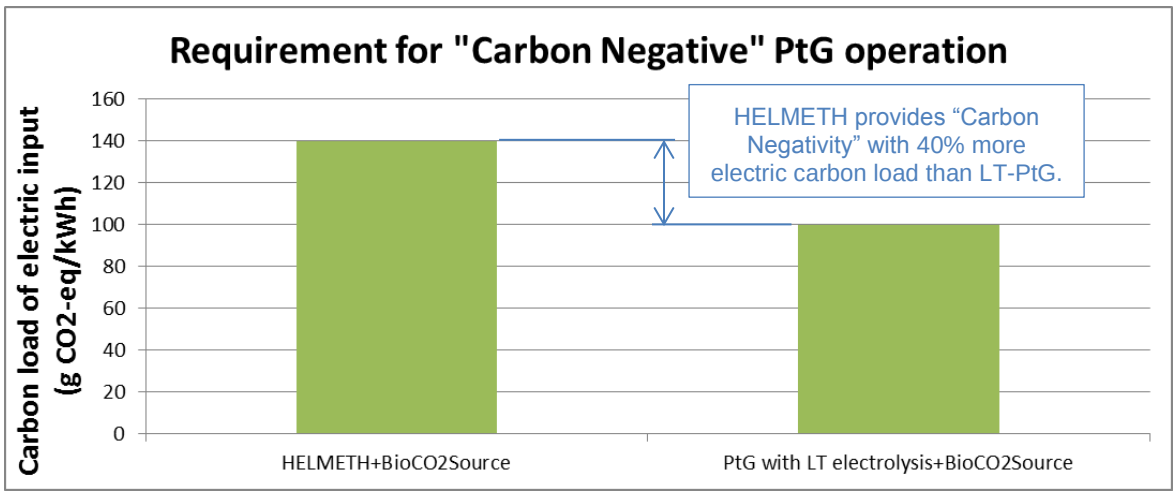

Figure 22 Electric carbon load requirements for Carbon Negative PtG operation.

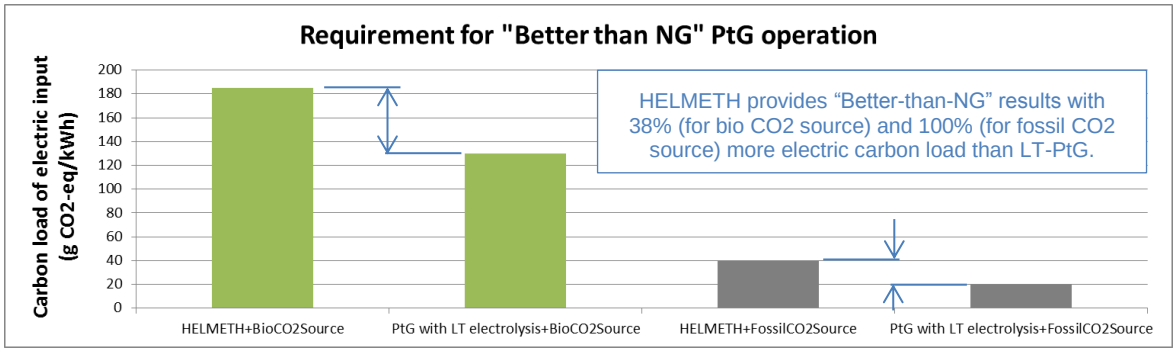

Figure 23 Electric carbon load requirements for Better-than-NG PtG operation.

5. Conclusion

The present analysis investigates the environmental impacts of the HELMETH concept system, in terms of Global Warming Potential for the production of 1 MJ of Synthetic Natural Gas. The results of CH_4 derived from Power-to-Gas were compared to natural gas extraction and transportation to Central Europe. Three key parameters have been identified that primarily influence the results:

- Electricity input. Relevant scenarios developed: Electricity generation from wind power, German electricity mix of 2020 and corresponding projection for 2050;
- CO_2 separation impact. Corresponding scenarios: CO_2 as waste product from biogenic sources (biogas and biomethane plants), from ambient air (DAC) or specific separation from the flue gases of coal/natural gas fired power plants and of industrial sources (cement/steel production and refinery);
- Electrolyzer (PtG) efficiency. The influence of the improved PtG efficiency provided by the High Temperature electrolysis/Heat Integration concept of HELMETH has been quantified, compared to standard PtG efficiencies from Low Temperature electrolysis technologies.

In order to provide a general overview of the GWP behaviour of the HELMETH concept system operation, the results of the abovementioned scenarios were interpolated in to one single contour diagram, covering a wide range of possible electric and CO_2 feeds. A complete "Carbon map" of the HELMETH concept system operation has been herewith developed, aiming to support the corresponding exploitation plan and in the last stage of the project, to provide added value to the business cases elaborated in parallel within WP5.

The major findings regarding the GWP of HELMETH SNG production were the following:

- Carbon negative operation is achieved by non-fossil CO_2 sources and an electric feed GWP of below 140-150 g CO_2-eq/kWh. Therefore, carbon negative operation is feasible, even with current or near future grid power input. In other words, a full renewable input is not a necessity.
- Lower GWP than extracting and transporting fossil NG is achieved by:
    - biogenic/atmospheric sources and electric carbon load of below 180-190 gr CO_2-eq/kWh and
    - fossil CO_2 source (however carrying only the corresponding compression impact) and a near fully renewable electric input (below 40 gr CO_2-eq/kWh).
- Existing PtG concepts powered by LT-electrolyzers feature higher requirements in terms of «clean» electric feed in order to achieve «Carbon negative» or «Better-than-NG» environmental performance. Relevant calculations show a requirement of 30% lower GWP of the electric feed, in order to reach the GWP vaules of PtG operation with HT-electrolysers.

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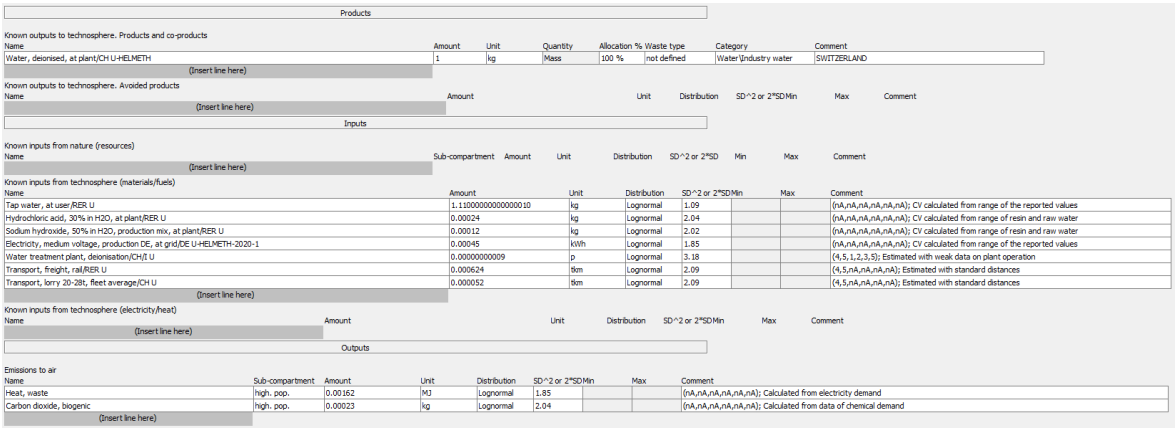

Products

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*SDMin	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*SDMin	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*SDMin	Max	Comment
(Insert line here)						

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SDMin	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 24 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.