Deliverable 5.1:
Initial LCA results on the “base case”
HEL METH concept system

PROJECT & ACRONYM: Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion (HEL M ETH)

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

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<tr>
<td>P2G/ PtG</td>
<td>Power-to-Gas</td>
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<tr>
<td>SNG</td>
<td>Substitute/Synthetic Natural Gas</td>
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<td>LCA</td>
<td>Life Cycle Analysis</td>
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<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
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<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>CO₂-eq</td>
<td>Carbon dioxide equivalent</td>
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<tr>
<td>H₂</td>
<td>Hydrogen</td>
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<tr>
<td>CO</td>
<td>Carbon monoxide</td>
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<tr>
<td>CH₄</td>
<td>Methane</td>
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<tr>
<td>H₂O</td>
<td>Water</td>
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<tr>
<td>PED</td>
<td>Primary Energy Demand</td>
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<td>NTP</td>
<td>Normal Temperature and Pressure</td>
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### Project partner acronyms

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<tr>
<td>KIT</td>
<td>Karlsruhe Institute of Technology</td>
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<tr>
<td>POLITO</td>
<td>Politecnico di Torino</td>
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<td>SUNFIRE</td>
<td>Sunfire GmbH</td>
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<td>ERIC</td>
<td>European Research Institute of Catalysis A.I.S.B.L.</td>
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<td>EEI</td>
<td>EthosEnergy Italia</td>
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<td>NTUA</td>
<td>National Technical University of Athens</td>
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<td>DVGW</td>
<td>DVGW - German Technical and Scientific Association for Gas and Water</td>
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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 m³ 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 CO₂ 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 CO₂ emissions in the next stages of utilizing (burning) the SNG (not shown in the present analysis).

Existing open issues (such as pressurization of CO₂ from bio-CH₄ output to the pressure requested by the HELMETH system, potential utilization of the produced O₂) 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 CO₂ 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 $1 \text{m}^3 \text{ (NTP)}$ 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 CO₂ either extracted from air or captured from a biogas plant or similar, are sufficient to produce a natural gas substitute.

In order to properly 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
- CO₂ 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 CO₂ supply plants and/or SNG grid injection near the Wind/PV plants are solved.

3.2. CO₂ Supply

The power-to-gas concept uses external carbon. CO₂ 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 CO₂ 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. CO₂ 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).
The waste CO₂ of a biogas upgrading process would be an interesting source for CO₂. The small share of CH₄ which is together with the CO₂ 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 CO₂ 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 CO₂ content (40% vol.) compared to flue gas
- Preferred CO₂ source in all running PtG research projects (According to (DGTC, 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, H₂ 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 (H₂, 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).

![Diagram comparing rated power, energy content, and discharge time of different EES technologies](image1)

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

![Diagram showing maturity and state of the art of storage systems for electrical energy](image2)

**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 (O₂ and H₂O) 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 m³ of SNG (Source: DoW)
4.1. CO₂ 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.
4.2. Water

The power-to-gas concept includes two production steps (see Figure 6): the water electrolysis to produce hydrogen (H₂) and the methanation which uses CO₂ to create CH₄ 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%.
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 CO₂ emissions caused by the three input flows considered (Electricity, CO₂ 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 CO₂ 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 m³ 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 CO₂ 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 CO₂ 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 CO₂ co-produced in a biomethane plant is associated to almost 2 kg of emissions per produced m³ of SNG, which is explained in Figure 13. Nearly all the emissions come from the production of biogas (0.835 kg fossil CO₂/kg CO₂ 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-CH₄). 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 CO₂ contribution of the CO₂ 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 CO₂ supply.
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-CH₄. The electricity input demands 86.8 MJ-eq/m³ 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.](image)

![Figure 15 PED for generation Scenario 2050-1 per energy source.](image)

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 CO₂ 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 “CO₂ 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-CH₄.

![Primary Energy Demand](image)

*Figure 16 Renewable and non-Renewable PED of 1 m³ 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 m³ 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-CH₄ 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 m³ 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 CO₂ 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 m³ 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 CO₂ emissions from fossil fuel sources and the Primary Energy Demand for the production of 1 m³ 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, CO₂ 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 CO₂ 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 CO₂ 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 CO₂ from bio-CH₄ output to the pressure requested by the HELMETH system, potential utilization of the produced O₂) 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 CO₂ sources) are to be addressed in the following stages of WP5.
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Figure 21 Datasheet for the production of 1 kg of CO₂ from biogas purification

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

Table 1 Electricity generation shares for the Scenarios examined.
<table>
<thead>
<tr>
<th>Non renewable, fossil</th>
<th>MJ-Eq</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(unspecified) Oil, crude, 38400 MJ per m³, in ground</td>
<td>38400 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, natural, in ground</td>
<td>40.3 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, off-gas, oil production, in ground</td>
<td>39.8 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, mine, off-gas, process, coal mining/ m³</td>
<td>39.8 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, natural, 36.6 MJ per m³, in ground</td>
<td>36.6 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, petroleum, 35 MJ per m³, in ground</td>
<td>35 MJ-Eq / m³</td>
<td></td>
</tr>
<tr>
<td>(unspecified) Gas, natural, feedstock, 35 MJ per m³, in ground</td>
<td>35 MJ-Eq / m³</td>
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<tr>
<td>(unspecified) Gas, natural, 35 MJ per m³, in ground</td>
<td>35 MJ-Eq / m³</td>
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<tr>
<td>(unspecified) Gas, mine, off-gas, process, coal mining/kg</td>
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<td></td>
</tr>
<tr>
<td>(unspecified) Gas, natural, feedstock, 46.8 MJ per kg, in ground</td>
<td>46.8 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Gas, natural, 46.8 MJ per kg, in ground</td>
<td>46.8 MJ-Eq / kg</td>
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<td>(unspecified) Oil, crude, in ground</td>
<td>45.8 MJ-Eq / kg</td>
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</tr>
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<td>(unspecified) Oil, crude, 42.7 MJ per kg, in ground</td>
<td>42.7 MJ-Eq / kg</td>
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</tr>
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<td>(unspecified) Oil, crude, 42.6 MJ per kg, in ground</td>
<td>42.6 MJ-Eq / kg</td>
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<td>(unspecified) Oil, crude, feedstock, 42 MJ per kg, in ground</td>
<td>42 MJ-Eq / kg</td>
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</tr>
<tr>
<td>(unspecified) Oil, crude, 42 MJ per kg, in ground</td>
<td>42 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Oil, crude, feedstock, 41 MJ per kg, in ground</td>
<td>41 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Oil, crude, 41 MJ per kg, in ground</td>
<td>41 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Methane</td>
<td>35.9 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Gas, natural, 30.3 MJ per kg, in ground</td>
<td>30.3 MJ-Eq / kg</td>
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<tr>
<td>(unspecified) Coal, 29.3 MJ per kg, in ground</td>
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<td>(unspecified) Coal, feedstock, 26.4 MJ per kg, in ground</td>
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<tr>
<td>(unspecified) Coal, 26.4 MJ per kg, in ground</td>
<td>26.4 MJ-Eq / kg</td>
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</tr>
<tr>
<td>Source</td>
<td>Conversion Factor (MJ-Eq)</td>
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<tr>
<td>-------------------------------</td>
<td>----------------------------</td>
<td></td>
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<tr>
<td>Coal, hard, unspecified, in ground</td>
<td>19.1 MJ-Eq / kg</td>
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<tr>
<td>Coal, 18 MJ per kg, in ground</td>
<td>18MJ-Eq / kg</td>
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<tr>
<td>Peat, in ground</td>
<td>13MJ-Eq / kg</td>
<td></td>
</tr>
<tr>
<td>Coal, brown, 10 MJ per kg, in ground</td>
<td>10MJ-Eq / kg</td>
<td></td>
</tr>
<tr>
<td>Coal, brown, in ground</td>
<td>9.9 MJ-Eq / kg</td>
<td></td>
</tr>
<tr>
<td>Coal, brown, 8 MJ per kg, in ground</td>
<td>8MJ-Eq / kg</td>
<td></td>
</tr>
<tr>
<td>Energy, from sulfur</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from peat</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from oil</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from gas, natural</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from coal, brown</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from coal</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Non-renewable, nuclear</td>
<td>MJ-Eq</td>
<td></td>
</tr>
<tr>
<td>Uranium, 2291 GJ per kg, in ground</td>
<td>2291000 MJ-Eq / kg</td>
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<tr>
<td>Uranium, in ground</td>
<td>560000 MJ-Eq / kg</td>
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</tr>
<tr>
<td>Uranium, 560 GJ per kg, in ground</td>
<td>560000 MJ-Eq / kg</td>
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<tr>
<td>Uranium, 451 GJ per kg, in ground</td>
<td>451000 MJ-Eq / kg</td>
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<tr>
<td>Uranium ore, 1.11 GJ per kg, in ground</td>
<td>1110 MJ-Eq / kg</td>
<td></td>
</tr>
<tr>
<td>Energy, from uranium</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Renewable, biomass</td>
<td>MJ-Eq</td>
<td></td>
</tr>
<tr>
<td>Energy, gross calorific value, in biomass</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from wood</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, from biomass</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Biomass, feedstock</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Renewable, wind, solar, geother</td>
<td>MJ-Eq</td>
<td></td>
</tr>
<tr>
<td>Energy, solar, converted</td>
<td>1MJ-Eq / MJ</td>
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</tr>
<tr>
<td>Energy, kinetic (in wind), converted</td>
<td>1MJ-Eq / MJ</td>
<td></td>
</tr>
<tr>
<td>Energy, geothermal</td>
<td>1MJ-Eq / MJ</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Renewable, water</th>
<th>MJ-Eq</th>
<th>(unspecified)</th>
<th>Water, barrage</th>
<th>0.01 MJ-Eq / kg</th>
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</thead>
<tbody>
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<td>(unspecified)</td>
<td>Energy, potential (in hydropower reservoir), converted</td>
<td>1</td>
<td>MJ-Eq / MJ</td>
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<tr>
<td>(unspecified)</td>
<td>Energy, from hydro power</td>
<td>1</td>
<td>MJ-Eq / MJ</td>
<td></td>
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