Supplementary Material

# Description of modeling of standardized scenarios

The provided inventories have been modelled with the LCA Software GaBi and some of the inventories[[1]](#footnote-1) could only be provided as a courtesy of Thinkstep (GaBi Software-System v8.5.0.79 and Database for Life Cycle Engineering SP 35 1992-2018). In the following, a description of the modelling is provided. Please note that the provided data sets do not aim to represent the status-quo or the future in an accurate way. Instead, the scenarios provided should help to avoid scenario generation for each LCA study and in addition, the scenarios allow a comparison between technologies as they serve as a harmonized input.

Four inventory data sets are provided:

1. Status-quo
2. Low decarbonized
3. High decarbonized
4. Full decarbonized

The scenarios have been generated by applying a simple rule: first, the greenhouse gas emissions of the electricity grid mix are computed and then the other technologies are selected such that the lowest greenhouse gas emissions are always achieved for each input. The only exception is the CO2 supply, in highly or fully decarbonized scenarios, as fossil power plants will no longer be available as a CO2 source. Instead, it is assumed that a direct air capture process supplies the CO2. In Table 3, the selected technologies are listed.

Table 3: Selected Technologies for scenarios

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Status quo** | **Low decarbonized** | **High decarbonized** | **Full decarbonized** |
| **Hydrogen** | Steam methane reforming | Alkaline electrolysis | Alkaline electrolysis | Alkaline electrolysis |
| **CO2** | Coal power plant | Coal power plant | Direct air capture | Direct air capture |
| **Heat** | Natural gas vessel | Electrode vessel | Electrode vessel | Electrode vessel |
| **Natural gas (methane)**  | Natural gas | Natural gas | Methanation  | Methanation |

### Electricity:

For the current electricity generation, the mix of electricity production for the EU is used from the GaBi database (EU-28: Electricity grid mix ts). For low and high decarbonized scenarios, the mix of electricity production for the EU is modelled according to the 2°C scenario of the Energy Technology Perspectives report for the year 2030 respectively 2050. The inventories for the electricity technologies are taken from the GaBi database (GaBi Software-System v8.5.0.79 and Database for Life Cycle Engineering SP 35 1992-2018). As inventories for European technology mixes are not available, inventories representing Germany are used as a proxy. In the Energy Technology Perspectives report, carbon capture and storage (CCS) technologies are used, but no inventories for the used CCS technologies are available. Therefore, electricity technologies with CCS are modelled as the same as conventional electricity technology, but greenhouse gas emissions from the IPPC WGIII AR5 are used instead of the original greenhouse gas emissions (Edenhofer 2014). In the full decarbonized scenario, electricity comes 100% from renewables and thus, wind energy is used as a proxy process (DE: Electricity from wind power ts) (GaBi Software-System v8.5.0.79 and Database for Life Cycle Engineering SP 35 1992-2018).

### Hydrogen

Currently, hydrogen is mainly produced by steam methane reforming of hydrocarbons. Therefore, for the status quo, production of hydrogen a steam methane reforming inventory has been used (DE: Hydrogen ts). For the hydrogen generation via electrolysis ,an alkaline water electrolysis has been modelled according to Koj et al. (Jan Christian Koj, Christina Wulf, Andrea Schreiber and Petra Zapp 2017). The impact of the electricity demand of the electrolysis is then calculated according to the energy scenario.

### CO2

For CO2 supply, two sources are considered: capture from exhaust gases of a coal-fired power plant (Schreiber et al. 2009) and direct air capture (von der Assen et al. 2013).

### Heat

Heat is either supplied by a natural gas boiler (EU-28: Heat ts) or by an electrode boiler. The electrode boiler simple converts electricity to steam with an efficiency of 95%. No other inventory was considered.

### Natural gas

Natural gas is either supplied by the natural gas network of Europe from the extraction of fossil natural gas or by methanation of CO2 and hydrogen

The natural gas network of Europe is modelled by weighting the national natural gas supply processes from the GaBi database according to their relative market volume in Europe. The market volume of the national gas markets are based on data from Eurostat and are assumed to remain constant over time (Eurostat). The following assumptions are made in the modelling of the natural gas network:

* For the national markets of Malta and Cyprus, no data is available. Thus, these countries are not considered in the EU natural gas mix.
* For the countries of Bulgaria, Croatia, Denmark, Estonia, and the Czech Republic, no national processes are available in the GaBi database (GaBi Software-System v8.5.0.79 and Database for Life Cycle Engineering SP 35 1992-2018). The national market of these countries combined contribute less than 4% to the total European market and are neglected.
* The market share of the other countries has been adjusted accordingly to reach 100%.

# Reporting

## Checklist - Executive summary

**Goal of the study**

* State the indented application of the study
* State the reasons for carrying out the study
* State the intended audience of the study
* State whether the results are to be used in comparative assertions disclosed to public
* State unambiguously the research question(s)
* State the classification of the assessed CCU technology

**Scope of the study**

* State functional unit clearly and unambiguously according to guideline and report changes due to solving of multi-functionality
* State system boundaries according to guideline
* State relevant issues with data quality and assumptions
* State technology readiness level (TRL) of processes and sub-processes
* Report production or storage capacity
* Report geographical scope
* State software system (and version) and data library (and version) used
* State type of review and provide additional information about reviewers

**Life cycle inventory and life cycle impact assessment**

* State main results of life cycle inventory and life cycle impact assessment
* If results are reported on a relative basis, report basis
* Describe uncertainty and sensitivity analysis and report results separately

**Interpretation**

* State any conclusions, recommendation and limitations

## Checklist – Main report

**Goal of the study**

* State the indented application of the study
* State the reasons for carrying out the study
* State the intended audience of the study
* State whether the results are to be used in comparative assertions disclosed to public
* State unambiguous research question(s)
* State the classification of the assessed CCU technology
* State limitations due to the assumptions and methods, e.g., if study is preliminary
* State commissioner of the study and other influential actors
* State technology readiness level (TRL) of processes and sub-processes
* Report production or storage capacity
* State review process and review experts, if any

**Scope of the study:**

* State functional unit clearly and unambiguously according to guideline, report changes due to solving of multi-functionality
* State performance characteristics, any omission of additional function in comparison and how performance is measured (might apply for products different in chemical structure and composition to their conventional counterparts)
* State system boundaries according to guideline and cut-off criteria including a system boundaries flow chart
* State omitted life cycle stages and processes (might apply for products different in chemical structure and composition to their conventional counterparts)
* State relevant issues with data quality and assumptions
* State method(s) to solve multi-functionality
* State impact assessment methods
* State data quality needs and how energy and material inputs and outputs are quantified
* State software system (and version) and data library (and version) used
* State type of review and provide additional information about reviewers

**Life cycle inventory**

* Include flow diagram of assessed process system(s)
* State types and sources of required data and information
* State calculation procedures
* State all assumptions made
* Describe sensitivity analysis for refining system boundaries
* Include calculated full LCI results (if this not contradicts with confidentiality)
* State data representativeness and appropriateness of LCI data
* If results are reported on a relative basis, report basis
* State results obtained from scenario analysis (including scenarios) and threshold values, if any

**Life cycle impact assessment**

* Include results of life cycle impact assessment
* State if impact categories coverage is reduced, e.g., in case of carbon footprinting
* If results are reported on a relative basis, report basis
* State if delayed emissions occur and include emission time profile if needed
* If applied, state discounting method and discounted results

**Life cycle interpretation**

* Include and describe the results
* Negative emission in cradle-to-gate studies shall not be interpreted as CO2 sinks if life does not end with permanent carbon fixation
* Emission reductions due to substitution effects shall be interpreted as environmental benefits but not as negative emissions.
* Describe uncertainty and sensitivity analysis and report results separately
* Include completeness check
* Include consistency check
* State assumptions and limitation associated with the interpretation of results
* Include conclusions
* Include recommendations, if any

## Technical Summary Table

|  |  |  |
| --- | --- | --- |
| **GOAL** | CCU product |  |
| Goal |  |
| Brief description |  |
| Intended audience |  |
| Functional unit |  |
| Limitations & assumptions |  |
| **SCOPE** | Boundary (i.e., cradle-to-gate) |  |
| Location |  |
| Time frames |  |
| Multi-functional approach | [ ] Sub-division[ ] System expansion[ ] System expansion via substitution[ ] Virtual sub-division[ ] Mass allocation | [ ] Energy allocation[ ] Economic allocation[ ]  Closed loop scenarios[ ] Other (please specify)………………… |
| **INVENTORY** | Data source | [ ] Primary sources[ ] Secondary sources[ ] Stoichiometric data | [ ] Process modelling based data[ ] Mixes sources[ ] Other (please specify)……………………. |
| Energy sources(select all that apply) | [ ] Grid mix[ ] Power station with Carbon Capture[ ] Wind[ ] Solar | [ ] Nuclear[ ] Hydro[ ] Future (see timeframes)[ ] Other (please specify)………………….. |
| Main sub-processes and TRLS | **SUB-PROCESS** | **TRL**TRL TRL TRL  |
| Database & software used |  |
| **ASSESSMENT** | LCIA method  | [ ]  CML[ ]  ILCD recommendation: v.\_\_\_\_[ ]  TRACI 2.0**OTHER IMPACT METHODS**[ ] ………………………………………… | **SINGLE CATEGORIES:**[ ]  Climate change[ ]  CED[ ]  use TOX |
| Highlighted results (graphical, text or tabular format) |  |  |
| **INTERPRETATION** | Main conclusions |  |
| Sensitivity analysis | [ ] No [ ]  Yes (please specify below) |

Literaturverzeichnis

Edenhofer, Ottmar (Hg.) (2014): Climate change 2014. Mitigation of climate change : Working Group III contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

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Jan Christian Koj, Christina Wulf, Andrea Schreiber and Petra Zapp (2017): Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. In: *Energies* 10 (7), S. 860. DOI: 10.3390/en10070860.

Schreiber, Andrea; Zapp, Petra; Kuckshinrichs, Wilhelm (2009): Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture. In: *Int J Life Cycle Assess* 14 (6), S. 547–559. DOI: 10.1007/s11367-009-0102-8.

von der Assen, Niklas; Jung, Johannes; Bardow, Andre (2013): Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. In: *Energy Environ. Sci.* 6 (9), S. 2721–2734. DOI: 10.1039/c3ee41151f.

1. LCIA results of the following processes are published with permission of Thinkstep: EU-28: Electricity grid mix ts, DE: Electricity from wind power ts EU-28: Heat ts, DE: Hydrogen ts [↑](#footnote-ref-1)