Green methanol

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CARBON
CHEMISTRY
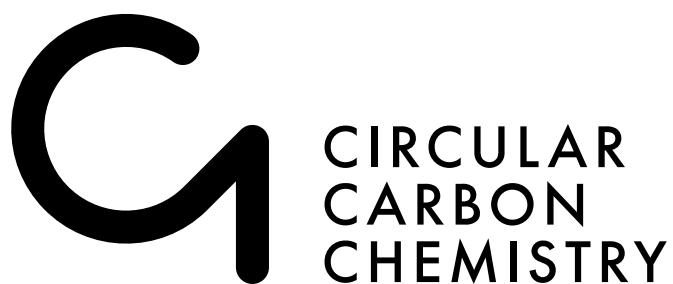
As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology is published for maximum transparency.

Terminology and abbreviations

AEL	Alkaline water electrolysis
CCS	Carbon capture and storage
CED$_f$	Cumulative fossil energy demand
CO$_2$-eq.	Carbon dioxide equivalents
DAC	Direct air capture: a process to extract CO2 from the atmosphere
Functional unit	Quantified performance of a product system for use as a reference unit
GHG	Greenhouse gas
HFO	Heavy fuel oil
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
MEA	Monoethanolamine
PEM	Proton exchange membrane
PtX	Power-to-X: synthesis processes providing numerous products using (renewable) electricity
RWGS	Reverse water gas shift reaction
SOEC	Solid oxide electrolyzer cell
WSI	Water stress index

In this report, the terminology "green methanol" refers to the methanol produced by C1's technology. The product is chemically identical to conventional methanol. In contrast to conventional methanol, usually made from natural gas or coal, green methanol is produced using alternative carbon sources such as CO$_2$ captured from the atmosphere or from flue gas, or carbon stored in biomass. Certain technologies to produce methanol require hydrogen, which can be supplied using electricity from renewable or non-fossil sources.

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Summary

Methanol is a widely discussed alternative to conventional fuels. For instance, shipping companies currently set-up methanol strategies to ramp-up the use of sustainably produced methanol. Aside from the shipping industries, methanol or fuels produced from it can be used as additives in liquid fuels in the road transportation sector. Aside from its use in the transportation sector, methanol is an important bulk chemical used to synthesize a wide range of products from plastics to solvents. At present almost all methanol is produced from fossil resources, such as natural gas and coal, accounting for 65 and 35% of the methanol production, respectively. **Due to its suitability to be used in the maritime sector and other transportation sectors, as well as due to its importance in the chemical industry, sustainable means of producing methanol will play a key role in the decarbonization of the economy.** C1, a Berlin-based company, developed a homogeneous catalyst that allows a highly efficient synthesis of methanol. Combined with renewable energy supply and a carbon source, such as biomass or captured CO_2, methanol can be produced without using fossil energy resources.

In this study, the potential environmental impacts of green methanol production is assessed. The assessment evaluates different synthesis routes that can be used with C1's technology. Several technologies to provide synthesis gas, such as the reverse-water-gas-shift reaction (rWGS), high temperature co-electrolysis (Ht-Co-El) and gasification are evaluated. Carbon is either obtained from biomass residues (gasification) or from CO_2 captured from the atmosphere or flue gas streams (rWGS and Ht-Co-El). Additionally, three types of electrolyzers are assessed. These electrolyzers provide hydrogen required by some of the synthesis routes. Eventually, sustainably produced methanol will displace conventional methanol (bulk chemical) or heavy fuel oil (HFO - maritime sector). Such displacement effects are taken into account in order to determine the **overall net changes in environmental impacts that could arise from a ramp-up of technologies, such as those offered by C1.**

The results show that C1 technologies are likely to result in a net decrease in GHG emissions ranging from 0.5 to 2.1 kg CO_2-eq. per kg methanol and **a net decrease in fossil energy demand ranging from 4 to 46 MJ per kg methanol**. **Other resource-demand related impact categories show an increase in indicator scores.** The demand for electricity from renewable sources is the main driver for the demand for resources. This is a trade-off inherent to many technologies relying on renewable energy supply. In view of the substantial reduction in GHG emissions needed, such trade-offs will need to be made to decarbonize the economy.

About C1

[C1](#) develops new, climate-friendly chemical production processes by rethinking chemical reactions from the atomic level all the way up to production scale. The chemical processes are designed with the help of quantum chemical simulations and implemented in proprietary production technologies. In doing so, the Berlin-based company develops and scales exclusively on the basis of renewable raw materials and energy. From the first steps in the development of a production process, all processes are designed to enable a closed carbon cycle. In this way, C1 supports industry on its way to net-zero.

As a first product, C1 has developed a fundamentally new proprietary homogeneous catalysis for the production of methanol. The C1 process is much more selective, productive and efficient than the heterogeneous catalysis currently in use, which dates back to a patent from 1921. It works at significantly lower pressure and temperature, allows for more flexible operations and scales better. There are cost advantages in terms of both investment and operating costs.

Table of content

1. About this study

The aim of this report is to provide insights into the potential environmental impacts of C1's green methanol production. **The assessment evaluates the potential changes in environmental impacts that might occur, if C1 enters the market and gains higher market shares.** Therefore, this study includes **all impacts related to the supply chain** of green methanol and its use, as well as potentially **displaced conventionally produced methanol or heavy fuel oil (HFO)**. The latter is considered because methanol is currently a widely discussed alternative to conventional fuels in the maritime sector. There are international shipping companies that have announced the use of methanol as a shipping fuel. As the assessment evaluates changes in environmental impacts, the applied life cycle assessment (LCA) approach follows a consequential LCA approach. Therefore, datasets reflecting marginal market changes are used whenever possible. By accounting for these effects, the study provides insights how environmental impacts might change if more green methanol is produced and used.

2. System description

The assessed system includes the production of methanol, the provision of feedstock and energy as well as the use of methanol as a fuel in marine shipping. Alternatively, methanol produced by C1 can displace conventional, fossil-based methanol. In such cases, the use phase and end-of-life, e.g. the treatment of products made from materials that were produced using methanol, do not differ. In this study, different supply chains for the supply of synthesis gas are evaluated:

- Reverse water-gas-shift reaction (rWGS) and hydrogen from electrolysis
- Biomass gasification
- High-temperature co-electrolysis (Ht-Co-El)

The produced synthesis gas is then converted to methanol via homogeneous catalysis. Methanol, used as a fuel, can be handled with existing infrastructure only requiring minor adjustments in the fuel supply chain. The use in ships might require other ship designs, e.g. larger tank volumes or the possibility to use other fuels, too (dual-fuel use). Alternatively, the use of methanol as a bulk chemical is assessed. The targeted (and assessed) market is the European market.

2.1. Functional unit and assessed indicators

The functional unit chosen is **1 kg of methanol used as a maritime fuel or as a bulk chemical**.

The system comprises feedstock supply, methanol production, distribution and use (Figure 1). Methanol produced by C1 is assumed to **replace conventional heavy fuel oil (HFO) used in the maritime industry and conventional methanol in the chemical industry**. The system is assessed using the indicators **climate change** (Intergovernmental Panel on Climate Change (IPCC) 2014) and several indicators related to resource use, i.e. **abiotic resource depletion** (CML - Department of Industrial Ecology 2016), **cumulative fossil energy demand** - CED_f (Verein Deutscher Ingenieure (VDI) (ed.) 2012), **land demand** and **water demand** - WSI (Pfister, Koehler, and Hellweg 2009).
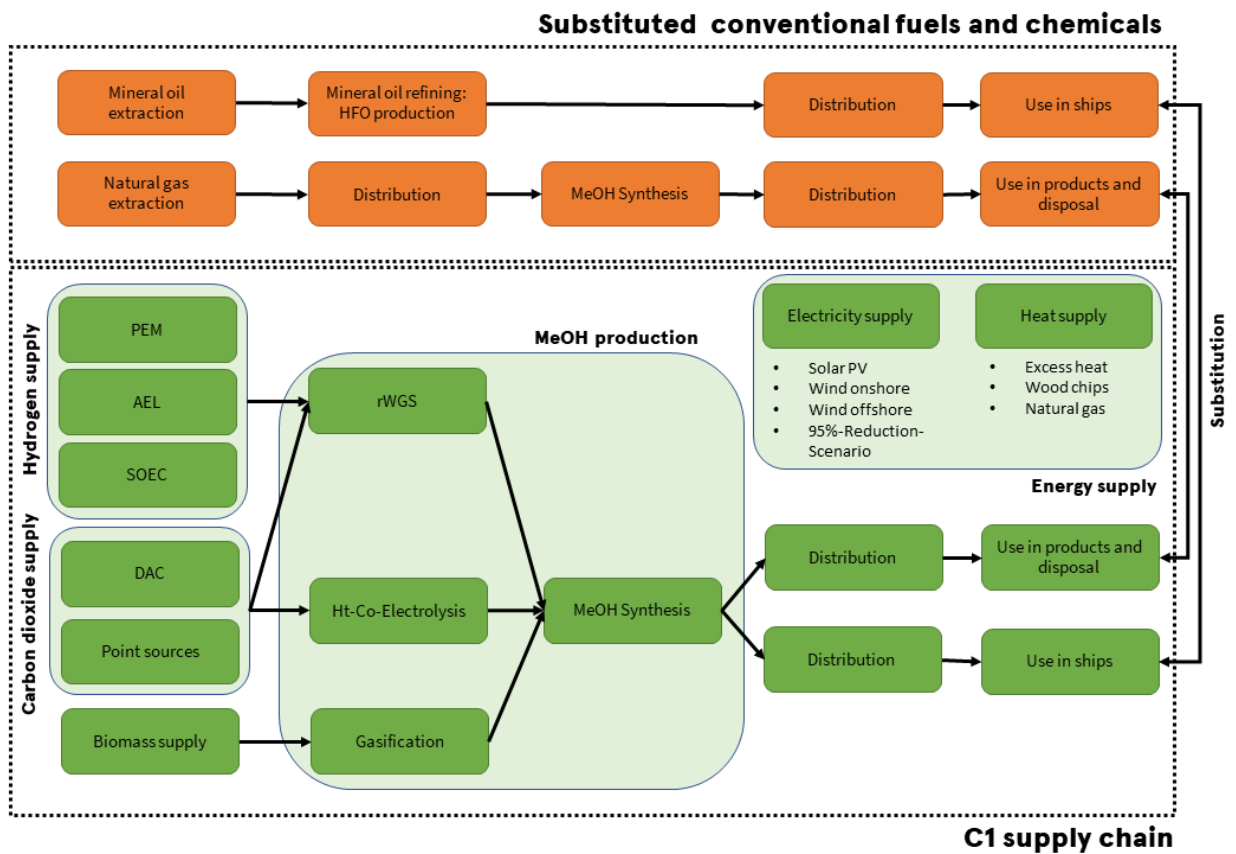
Figure 1 *Depiction of system boundaries. Green processes will begin/increase/change in operation if C1 enters the market; orange processes will cease to operate or reduce their production. Different supply chains for the provision of hydrogen and carbon dioxide are assessed. Different future electricity supplies are modeled. Background processes, e.g. raw material supply, infrastructure, waste treatment, etc. are not depicted. Abbr.: AEL - Alkaline electrolysis, DAC - Direct air capture, HFO - Heavy fuel oil, MeOH - Methanol, PEM - Proton-exchange-membrane, PV - Photovoltaics, rWGS - Reverse water-gas-shift reaction, SOEC - Solid oxide electrolysis cell.*

2.2. Description of the supply chain elements

In the following section, the key elements of the supply chains depicted in Figure 1 will be explained. Most important technical parameters are described. Detailed life cycle inventory tables are provided in the Annex.

2.2.1. Hydrogen supply

At present, hydrogen is mostly supplied by steam reforming of natural gas. In future, hydrogen is likely to be supplied by water electrolysis. Several potential electrolysis technologies are currently available on the market and/or being developed (O. Schmidt et al. 2017; Subramani, Basile, and Veziroğlu 2015).

- **Proton exchange membrane (PEM):** A PEM electrolyzer comprises an electrolyte that conducts protons. At the anode, water is converted to a proton (H^+), molecular oxygen (O_2) and electrons. The proton passes through the membrane to the cathode, where it is converted to hydrogen. PEM electrolyzers usually operate at low temperatures (between 50 and 80°C) and at pressures below 200 bar. They are able to run at flexible capacities and exhibit a cold start of less than 20 minutes. The advantages of PEM electrolyzers are the highly compressed pure hydrogen product and the flexible operation at different loads. The disadvantages of PEM are (at the

present state of development): catalyst (e.g. platinum) and membrane material costs, water purity requirements and the complexity (compared to the other types).

- **Alkaline water (AEL) electrolyzers:** In the AEL process, water is converted into hydrogen and hydroxide (HO^-) at the cathode. The hydroxide ions travel through the electrolyte (an aqueous solution containing an alkali, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH)) to the anode, where oxygen and water are produced. Another well-established concept is the chlor-alkali electrolysis. In this process, the cathode reaction is the same. At the anode side of the electrolyzer, chloride ions (Cl^-) from a sodium chlorine solution are oxidized to chlorine. Na^+ passes through a selective membrane to the cathode, where sodium hydroxide is formed. The process yields hydrogen, chlorine gas and sodium hydroxide. The chlor-alkali electrolysis is widely used to produce chlorine and sodium hydroxide. Alkaline electrolyzers usually operate at low temperatures (below 100°C) and low pressures (below 30 bar). The advantages of these systems are the relatively low capital costs and mature technology. The AEL modeled in the assessment requires $2.5 \cdot 10^{-3}$ kg potassium chloride per kg hydrogen (Delpierre et al. 2021).
- **Solid oxide electrolyzer cells (SOEC):** In an SOEC, water is converted to hydrogen and oxygen ions (O^{2-}) at the cathode. A ceramic material serves as an electrolyte that transfers oxygen ions to the anode, where it is converted to molecular oxygen. SOEC operate at high temperatures (~500 to 950°C). SOEC have a high electrical efficiency and a low load flexibility.

SOEC entered the market only recently. A critical aspect is the efficiency of electrolyzers. Learning effects will result in an increase in efficiencies of electrolyzers in the upcoming years (International Renewable Energy Agency 2020). There is a wide range of stack and system efficiencies of different electrolyzer technologies reported in literature. Based on a literature review, electrical system efficiencies of 70, 70 and 80% were assumed for PEM, AEL and SOEC (Liebich et al. 2020; Häfele, Hauck, and Dailly 2016; Delpierre et al. 2021; International Renewable Energy Agency 2020). The capacity of the electrolyzers is 1 GW. A stack life-time of 10 years and a system life-time of 30 years was considered. Detailed inventory tables of the electrolyzers can be found in Tables A.1. to A.3 in section A.1.1 of the Annex.

2.2.2. Carbon dioxide supply

CO_2 or CO can be obtained directly from the atmosphere or from industrial point sources (Cuéllar-Franca and Azapagic 2015).

- **Direct air capture:** currently, DAC is the most discussed option to directly obtain CO_2 from the atmosphere. The technologies usually use an absorbent (e.g. amine-based or caustic sorbent) or adsorbent to absorb/adsorb CO_2. In a subsequent step, CO_2 is desorbed and compressed.
- **Point-sources providing CO_2:** Certain industrial processes produce large amounts of CO_2 due to the combustion of (fossil) fuels or as a result of other chemical reactions. The main source of anthropogenic CO_2 is fuel combustion (e.g. power plants, refineries, kilns etc.). In addition, other processes emit process-based CO_2. For example, clinker production emits large amounts of CO_2 in the process of calcination (converting calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and CO_2). Additionally, there are many biogenic processes used in industrial applications using biogenic feedstock to produce food, feed, chemicals, energy or fuels producing CO_2 as a metabolic or process-related side-product, e.g. ethanol production and anaerobic digestion. In addition, the combustion of carbonaceous biofuels emits CO_2 that can be captured and utilized. For instance, solid biomass or biomethane can be combusted in power plants to supply process

energy or base-load energy supply. There are numerous technologies to obtain CO_2 from any point source mentioned, such as absorption by chemical solvents, adsorption by solid sorbents (e.g. zeolites), membrane separation, pressure/vacuum swing adsorption.

In this study, both of these technologies are assessed. The DAC units use an adsorption-desorption of CO_2 on filter material (cellulose with amines). Such systems are currently developed by Climeworks. The data used in this study was taken from (Schreiber et al. 2020) and relates to an existing Climeworks installation. Among potential point sources, cement factories are likely to be the major supply of CO_2 in future (in case a substantial reduction in GHG emissions are achieved in the energy and manufacturing industries) (Thonemann and Pizzol 2019). A CO_2 capture based on monoethanolamine (MEA) absorption is assessed in this study based on the inventory provided in (Giordano, Roizard, and Favre 2018). The LCI of these two technologies is listed in Tables A.4 and A.5 in section A.1.2 of the Annex.

2.2.3. Biomass supply

In addition to the supply chains using hydrogen from electrolysis and captured CO_2, an alternative supply route is assessed: gasification of forest residues. Forest residues are collected, chipped and transported to a central gasification and synthesis facility. The wood residues are transported 10 km in the forest by tractors and 50 km by truck on the road. In literature, no negative effects on the soil organic carbon content is reported (Brassard, Godbout, and Hamelin 2021; Giuntoli et al. 2015).

2.2.4. Conversion and synthesis

Three different technologies are evaluated to provide synthesis gas:

- **rWGS:** In a rWGS reactor, synthesis gas can be obtained from CO_2 and H_2. Additional H_2 is added to obtain the appropriate H_2 to CO ratio to synthesize methanol in a subsequent step. The LCI of the rWGS reactor and reaction was used from (Sternberg and Bardow 2016). The inventory is listed in Table A.6 in section A.1.3 of the Annex.
- **Ht-Co-electrolysis:** The high-temperature co-electrolysis is a technology to directly obtain synthesis gas from water (steam) and CO_2. The data used in this study is data from Linde AG as part of the Kopernikus Project (Schreiber et al. 2020). The Ht-coelectrolysis electrolysis has an electrical efficiency of 0.75 (Schreiber et al. 2020). The lifetime of cells, stacks and the plant are 3.2, 5 and 20 years, respectively. A 150 kW unit contains two stacks with 960 cells each. The input of hydrogen and CO_2 was calculated based on a stoichiometric ratio of H_2:CO of 2:1. The inventory data of cells, stacks and the plant are listed in Tables A.7 to A.10 in section A.1.3 of the Annex.
- **Gasification:** One evaluated supply chain uses gasification to provide syngas. In the gasification plant, the biomass (forest residues) is heated to high temperatures without combusting it. This results in a volatilization of volatile compounds and the decomposition of biogenic structures. Part of the synthesis gas is combusted to provide the required heat. The data used stems from the GoBiGas project, a 20 MW fist-of-its-kind gasification plant in Gothenburg. There are numerous publications providing detailed process data that was used to compile the LCI, cf. (Ahlström et al. 2019; Alamia et al. 2017; Larsson, Gunnarsson, and Tengberg 2018; Thunman et al. 2018). The process, if optimized, does not require any additional external energy (Thunman et al. 2018). The full inventory is listed in Table A.11 in the Annex.

In all cases, the synthesis gas is converted to methanol using a homogeneous catalysis developed by C1. Due to the homogeneous catalyst, milder process conditions can be applied. The catalyst is highly selective and product separation can be easily conducted. A similar catalyst as reported in these studies is used (Kaithal, Werlé, and Leitner 2021; Ryabchuk et al. 2019). The performance of the catalyst was assessed by an independent research institute. The catalyst composition, its selectivity and the catalyst composition are known to Planet A. Due to confidentiality reasons, this information cannot be disclosed in this report. Finally, methanol is separated from the catalyst and purified. The purification can be achieved using molecular sieves. A lifetime of 20 years was assumed for the facility.

2.2.5. Methanol distribution and use

In this study, a use of methanol as transportation fuel in the shipping industry is assessed. Methanol can be used with existing fuel distribution systems with minor modifications. In ships, methanol can be used in combustion engines and in fuel cells. Yet, it is unknown where production facilities will be located and how infrastructure will change. Potentially, they could be located at ports making most of the existing efforts to transport fuels to ports obsolete. However, since this is uncertain, no changes in fuel distribution are assumed.

2.2.6. Energy supply

Several combinations of electricity and heat supply are assessed. Electricity is either supplied by onshore or offshore wind power, solar PV or a combination of the former generation options with natural gas in a variant representing a potential future energy mix compatible with a 95% GHG emission reduction and a full-time availability (8760 hours per year) (Bareiß, Schönleber, and Hamacher 2018). This mix consists of 66% wind energy, 29% solar PV and 5% natural gas. The environmental impacts of electricity supply were taken from a recent United Nations Economic Commission for Europe publication assessing environmental impacts of global electricity supply (United Nations 2021). The study provides the impact of electricity supply considering local conditions, e.g. solar irradiation, wind speeds and the impact of local energy production. Furthermore, technological advances and learning effects, such as scale and technology learning are considered. In this study, the data for Europe is used[1].

The assessed CO_2 capturing technologies require heat to desorb CO_2. In this study, several different heat supply options are considered: excess waste heat from industrial processes, wood biomass and natural gas. These scenarios reflect a likely case (these units will be deployed where cheap excess heat is available) and two other cases using a renewable choice (wood biomass) and a fossil energy source (natural gas) are considered. It should be noted that the European Commission plans to tighten rules regarding the use of woody biomass for energy production (European Commission 2021). If the proposal is transposed into law, biogenic CO_2 emissions from cultivated biomass are likely to be fully counted in the GHG certification method, making it harder to achieve the required *GHG savings* threshold. The underlying idea is to use woody biomass in other sectors than the energy sector. The new requirements apply to the energy and transportation sector and not the bio-based material sector. Hence, methanol used as a fuel could be affected, whereas methanol used as a bulk chemical is not affected by these rules.

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[1] The reader is referred to (United Nations 2021) for the full description of the datasets and the environmental impact of electricity supply.

2.2.7. Displaced conventional products

Two potential key markets of green methanol are assessed in this study: the chemical industry where methanol is used as a bulk chemical and the maritime sector where methanol is considered as a viable alternative to heavy fuel oil (HFO). Today, methanol is also used in other transport sectors than the shipping industry. In this study, the shipping industry was selected because at the moment logistic companies are working on creating a market for green methanol to be used in container ships. Thus, sustainable methanol will play an important role in the future maritime logistics. The data for conventional methanol and HFO production was taken from the Ecoinvent database (Wernet et al. 2016). Conventional methanol is produced by steam reforming of natural gas and subsequent methanol synthesis. The process has an overall carbon efficiency of 75% (81% synthesis gas production and 93% for the methanol synthesis) (Wernet et al. 2016; Althaus et al. 2007)[2]. Electricity needed in the process is provided by using excess heat of the steam reforming process.

The future locations of C1's production facilities are not known to date. Hence, an assessment of changes from the current state of methanol and HFO supply infrastructure to a possible supply of C1's methanol to where the methanol is used, is not possible. Therefore, no change in transportation of HFO/methanol or conventional/green methanol are considered. Green methanol can fully substitute conventional methanol in the chemical industry. If methanol is used as a shipping fuel to displace HFO, minor modifications in the fuel infrastructure and several technical modifications onboard are also required. No data is available on material and energy use required to retrofit existing ships. Therefore, these aspects were neglected. Currently, logistics companies, such as MAERSK already plan to order new methanol-fueled ships. It is assumed that these ships will replace conventional ships after the end of their service life. As this assessment follows a consequential LCA approach seeking to assess the changes occuring as a result of green methanol supply by C1, replacing ships with newer ships without a shortening of the lifetime of the decommissioned ships, does not result in a change in emissions if it is assumed that the production of the methanol-fueled ship results in similar environmental impacts as another, e.g. conventional ship, that would have been built instead, if the methanol ship had not entered the market. Yet, no inventory data for methanol-fueled container ships is available. It was therefore assumed that new methanol ships replace conventional ships after their regular lifetime without changing the environmental impact of ship production. Studies indicate a minor improvement of the fuel efficiency ranging from 1-2 % (DNV GL 2016). In this study, a value of 1.5 % was used. The amount of conventional HFO displaced by green methanol was determined according to the energy content of both fuels.

2.3. Accounting of GHG emissions from methanol use or its end-of-life

Methanol used as a maritime fuel is combusted resulting in the formation of CO_2. If the assessed methanol is used as a chemical (for the synthesis of other chemical products), it will be disposed of as those products that formerly used conventional fossil methanol. In certain cases, this might result in a release of CO_2, e.g. if products are incinerated or oxidized by other means. How these releases of CO_2 are assessed within this study, depends on its origin:

If **atmospheric CO_2** is used to produce methanol, CO_2 can either be captured from the atmosphere using DAC or photosynthesis, respectively. In both cases, the amount of CO_2 captured approximately equals the amount of CO_2 that is emitted to the atmosphere when the PtX products are used.

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[2] The ecoinvent license restricts the publication of full data tables. The reader is referred to the current Ecoinvent database and (Althaus et al. 2007) for detailed information on the dataset.
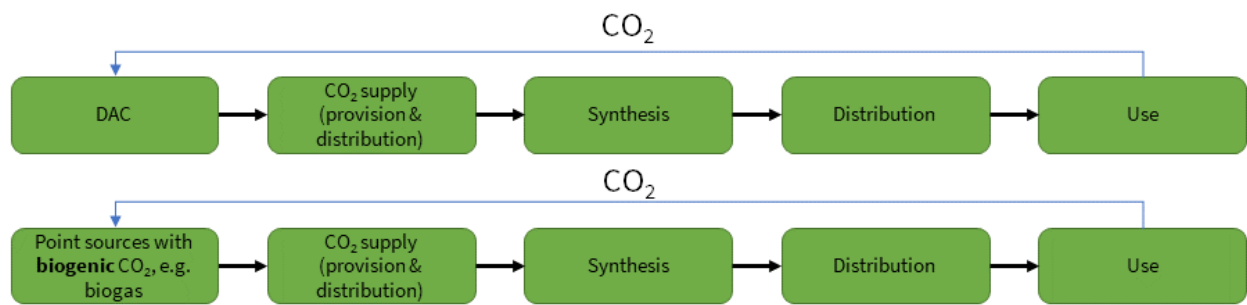
If **biogenic carbon** sources are used, temporal aspects might be relevant: if wood is used, it will take several years until the same quantity of CO_2 is stored in wood again. This might result in a burden shifting to future years.

CO_2 of fossil origin can also be used to synthesize PtX products, for example, CO_2 captured in flue gas from fossil fuel powered power plants or captured from cement factories. In contrast to the previously discussed scenarios there is no closed loop in such cases.
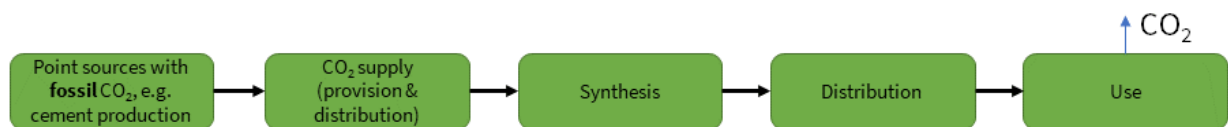
These schemes refer to the use of methanol used as a fuel. In such cases, methanol is combusted and CO_2 is released to the atmosphere again. In case methanol is used as a bulk chemical, methanol is likely to be converted to chemicals or products that end up in the economy where they remain for a certain time: for instance, resins or plastics might remain in the economic system for several years until they are finally disposed of. In such cases, the CO_2 converted to methanol remains out of the atmosphere for a certain period of time. This is a temporary carbon sink reducing the warming effect on the climate during the storage period. Due to the uncertainty of the fate of all products made from methanol and the minor effect on the climate (considering the short duration of storage), these temporal storage effects are not accounted for.

In case the product is landfilled, the carbon is stored for an even longer time. In such cases, carbon is stored for time periods that can have a substantial effect on the climate. Such long-term storages would result in negative carbon emissions to be additionally benefiting the green methanol. With consideration of when C1 might play an important role in decarbonizing the chemical or shipping industry, landfilling is an undesirable way of disposing waste (if a circular economy operating within the planetary boundaries is desired). Additionally, the fate of all products made from methanol is not known. The results presented in this study are a conservative case without such a long-term storage of CO_2.

The question arising from these examples is how CO_2 emissions from fuel use should be attributed. This depends on the perspective:

a) **Attributional LCA approach: Allocating GHG emission to different products or parties**

For certification purposes or emission trading, it might be required to allocate emissions to specific elements in the supply chain. Using the above examples, it is of considerable interest, who is responsible for CO_2 emissions from methanol use or its end-of-life: is the cement factory

responsible for these CO_2 emissions or is it the user of the product (or any other party that is responsible for producing, selling, distributing or using the fuel)? In order to avoid loopholes in GHG emission accounting, one party within the supply chain must be held accountable for these emissions. If such an allocation is required, there would not be any emissions from methanol product use to be allocated in case of the first two examples because there is a closed (accounting) loop. Using this approach, emissions of other processes that are not part of the overall supply chain do not matter.

b) Consequential LCA approach: Assessment of changes in GHG emission in the overall economic system

In the consequential LCA the assessment seeks to assess the net changes of GHG emissions (or other environmental indicators and impacts) as a consequence of a certain change in the system, e.g. the start of wide-scale green methanol production.

In the first two examples, there is a closed loop and no net emissions from product use or disposal occur if green methanol is produced and used. The same quantity of CO_2 is captured (by plant or by DAC) that is emitted by its use or disposal. In the third example, the CO_2 emitted through the use of the green methanol or the product containing the green methanol is the same CO_2 that would have been emitted by the industrial point source, if the methanol facility did not exist. The methanol supply chain is a cascade use of the CO_2 emitted by the industrial point source. Hence, the introduction of the green methanol supply chain does not alter the volume of this particular CO_2 stream. In all three examples, a ramp up of green methanol production does not affect CO_2 emissions emitted by existing emitters in the existing system.
Caveat: This assumption is valid as long as there is no wide-scale use of carbon capture and storage (CCS) technologies. If CCS became a standard in the industries, the use of CO_2 for methanol production (or any other uses, e.g. power-to-liquid or power-to-gas fuels, would lead to the avoidance of the long-term storage of CO_2.

Which approach is chosen in this assessment and why?

The purpose of this report is to evaluate potential **changes in GHG emissions (and other indicators) as a consequence of the start of wide-scale green methanol supply and use**. These changes comprise all emissions emitted within the supply chain and changes in emissions occurring in other sectors of the economy. Hence, the report considers the replacement of (fossil) counterparts. The previous examples show that CO_2 emissions from other point sources are likely to remain unaffected. Therefore, there is no differentiation made between CO_2 derived from DAC and from point sources regarding the way CO_2 is treated in the GHG balance. Approach b) as described above is applied.

It is strongly emphasized that this approach does not serve certification or accounting. In such cases, fossil CO_2 emitted must be allocated to processes within the supply chain (either to the point source or to the sector in which the product is used, e.g. the transportation sector). It is also important to note that the (political) decision to promote certain supply chains might entail long-term consequences for the ambitions to reach net zero GHG emissions at a certain point in time globally. To achieve this, all sectors must decrease GHG emissions. Promoting the cascade use of CO_2 from point sources that emit fossil CO_2 might prolong the existence of such point sources. Hence, from a holistic perspective, promoting CO_2 use from fossil point sources should only be considered in those cases where emission

reductions are not possible and where no alternative to these processes exists (e.g. calcination in cement production).

3. Environmental impact of methanol supply and use

In total, the several variants were assessed to cover a wide range of technologies and energy suplly scenarios:

- 12 different energy supply variants
  - electricity: wind onshore, wind offshore, solar PV and a 95%-GHG-reduction mix
  - heat: excess waste heat, wood chips and natural gas
- 9 technical setups
  - rWGS: PEM, AEL and SOEC electrolyzer with DAC or CO_2 from a point source
  - Ht-Co-electrolysis with DAC or CO_2 from a point source.
  - Biomass gasification: This configuration is energy self-sufficient. Hence, there is no difference between the different energy supply variants.

In the following sections, the environmental impacts of green methanol production are discussed first (section 3.1). In section 3.2, the environmental impacts of conventional methanol supply and its use are presented. Lastly, the potential net changes in environmental impacts arising from a ramp up of C1 are discussed in section 3.3. In such a case, the environmental impacts discussed in section 3.1 arise, whereas impacts discussed in section 3.2. are avoided.

3.1. Environmental impact of green methanol production

In this section, the impacts of methanol production are discussed in detail. In the subsequent section, the overall net change in impacts resulting from a market introduction of green methanol is discussed, i.e. including displacement effects. <u>Please note</u>: The following diagrams show a selection of technologies using a 95%-GHG-reduction electricity mix with all heat supply variants. In the following diagrams, only one electrolyzer type (PEM) is depicted. The diagrams visualize the differences in the different heat supply variants and the different technologies (electrolysis, co-electrolysis and gasification) and to provide some visualization of the contribution of different elements in the supply chain. The results discussed in the text refer to all assessed variants (not just those presented in the diagrams). All results are presented in section A.2 of the Annex.

3.1.1. GHG emissions
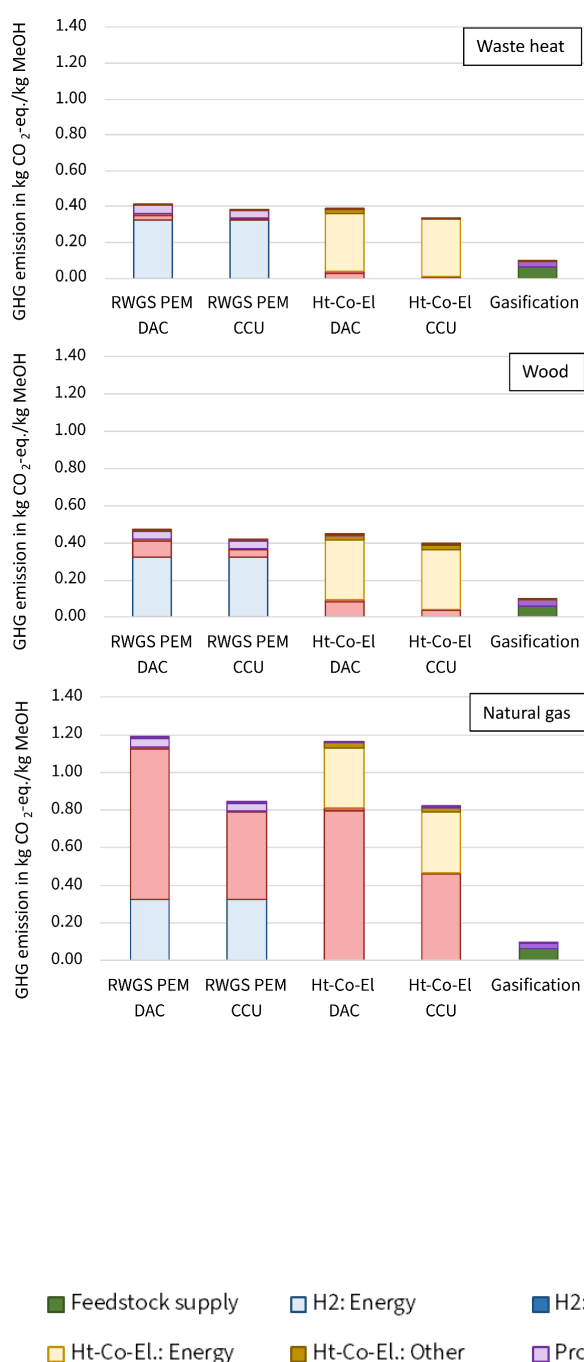
The supply of green methanol using captured CO_2 results in GHG emissions ranging from 0.12 to 1.18 kg CO_2-eq. kg methanol. The range is caused by the GHG intensity of different energy supply variants: energy supply is by far the most important contributor to GHG emissions accounting for more than 74% of the GHG emissions in all assessed variants of the variants using electrolysis (water electrolysis and co-electrolysis). Using natural gas for heat supply more than doubles the GHG emissions in most cases: all variants in which heat is supplied by using waste heat or biomass[3] emit less than 0.5 kg CO_2 per kg methanol, whereas those variants in which heat is supplied using natural gas result in GHG emissions above 0.59 kg CO_2-eq. The setup using biomass gasification emits considerably lower GHG emissions (0.1 kg CO_2-eq per kg methanol). Biomass supply accounts for 35% of these emissions. The remainder comes from consumables used in the gasification step. The catalyst used by C1 and the infrastructure only have a minor influence on results. These results show that the most determining factor of C1 production will be energy supply, if a setup is chosen that relies on captured CO_2 and (co-)electrolysis.

Therefore, these types of technical setups should rely on energy supply with low associated GHG emissions. In contrast, biomass gasification results in much lower GHG emissions and is clearly the most favorable variant in terms of GHG emissions.

Figure 2 *GHG emissions of green methanol production. The diagrams show 5 different technical setups (rWGS with hydrogen from PEM electrolysis combined with CO_2 supply from DAC or flue gas stripping, high temperature co-electrolysis with CO_2 supply from DAC or flue gas stripping and biomass gasification) with three heat supply variants (excess waste heat (top), wood chips (middle) and natural gas (bottom)). In all cases, electricity is supplied by a supply mix compatible with a 95% GHG emissions reduction in the energy sector. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, NG - Natural gas, PEM - Proton exchange membrane.*

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[3] If green methanol is to be used in the transportation sector in the EU, the produced methanol needs to fulfill certain requirements of the Renewable Energy Directive II. For instance, the use of residual wood (instead of cultivated primary wood) might be required to achieve the *GHG saving* defined in the Renewable Energy Directive II if the current proposal is transposed into law (section 2.2.6). The European Commission has yet to define a methodology to assess *GHG savings* of renewable fuels of non-biological origins. If the green methanol is used in other sectors, these requirements do not apply.

3.1.2. Resources

3.1.2.1. Abiotic resources
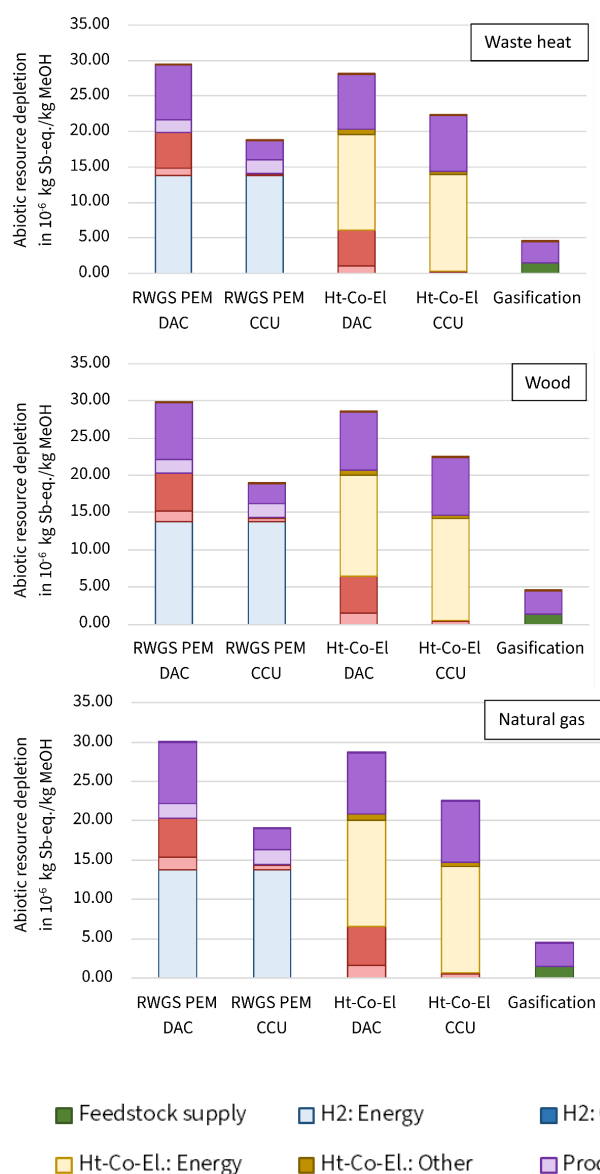
Abiotic resource use is dominated by infrastructure requirements. This includes materials needed to build renewable energy infrastructure, electrolyzers and DAC units. The impact category does not include energy resources (see section 3.1.2.2. below), therefore, there is only a very minor difference in the different heat supply variants. There is a notable difference between different electricity sources: if electricity is supplied by solar PV, the abiotic resource demand is around twice as high as if electricity is supplied by wind[4]. Setting up a new supply chain or increasing the demand for energy and infrastructure will eventually result in the additional demand for resources. This demand for resources can be alleviated at a later point in time, when materials are recycled (if possible). Among the assessed electricity supply technologies, solar PV performs the worst. Again, the gasification setup performs much better than the other supply chain setups using (co-)electrolysis. Therefore, this concept is also to be preferred in terms of resource demand.

Figure 3 *Abiotic resource depletion of green methanol production. The diagrams show the same supply variants and energy supply scenarios as depicted in Figure 2. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, PEM - Proton exchange membrane.*

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[4] Please note: This statement refers to the indicator abiotic resource depletion, which considers resource scarcity and availability. Therefore, the indicator values include more than just the total mass of materials used. For further details, please see (CML - Department of Industrial Ecology 2016).

3.1.2.2. Fossil energy resources
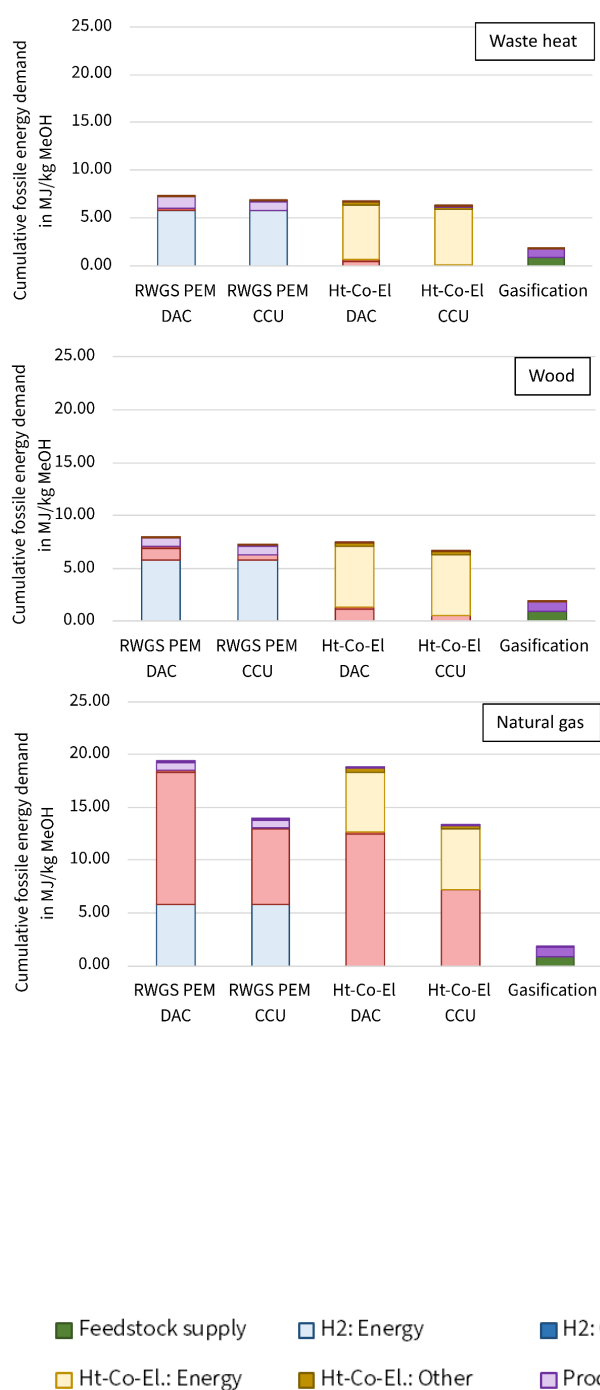
All variants require low amounts of fossil energy as long as heat and electricity is supplied using renewable energy sources. The fossil energy demand of supply variants using renewable energy mainly stems from energy that is needed to manufacture all materials needed. In the 95%-GHG reduction scenario, even the low share of natural gas in the electricity mix results in a substantial increase in fossil energy demand. In these scenarios, the fossil energy demand doubles to triples. The datasets available reflect current production modalities. This is an important aspect to consider because infrastructure to be built in a future industry that is defossilized is likely to require less fossil energy resources. These developments are yet to take place. Therefore, the presented results present a conservative case, assuming that the fossil energy input in infrastructure and material manufacturing remains on today's levels. In addition to infrastructure, there are consumables used that are currently manufactured using fossil energy (e.g. adsorbent used in the DAC unit). The methanol synthesis reaction is an exothermic reaction not requiring external energy. Energy is required to operate the equipment. Even considering a present economy still relying largely on fossil energy, green methanol production only requires a fraction of the energy supplied.

Figure 4 *Cumulative fossil energy demand of green methanol production. The diagrams show the same supply variants and energy supply scenarios as depicted in Figure 2. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, PEM - Proton exchange membrane.*

3.1.2.3. Land use
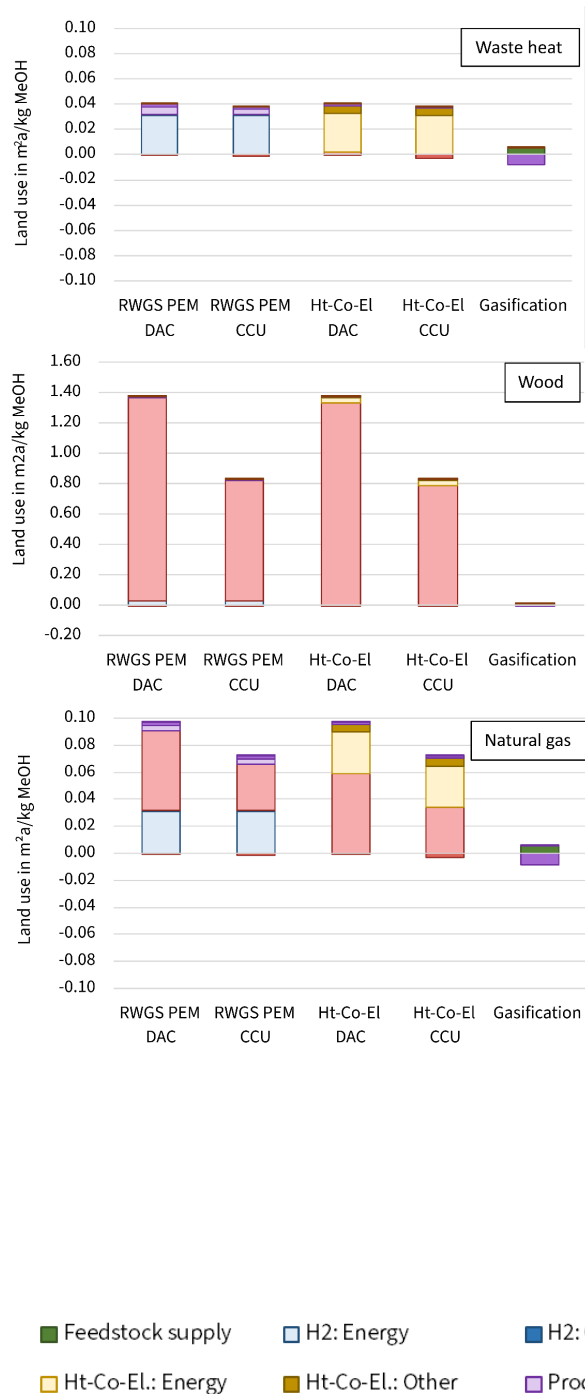
The land-use of methanol production is dominated by electricity supply in case excess waste heat is used. The land demand increases substantially if cultivated biomass is used to provide heat. Among electricity supply variants, solar PV has the highest space requirements (see section A.3 in the Annex). The space requirements for biomass cultivation exceeds all other land requirements by far. The negative land use requirements arise from consumables that provide other products when produced. For instance, the gasification process requires rape methyl ester. The production of rapeseed oil also provides rape meal, which is a high protein feed. Thus, increasing the demand for rapeseed methyl ester eventually increases the supply of high protein feed. This might result in displacement effects. Likewise, other consumables used in the other variants, provide co-products which displace other products.

As stated in section 2.2.6 and footnote 3 above, upcoming legislation is likely to promote the use of woody biomass for other purposes than energy production. Hence, using cultivated wood to provide heat is only eligible if the methanol is used in the chemical industry and not in the energy sector. If wood residues were used (to comply with the potential new requirements of the Renewable Energy Directive II), the overall land requirements would be much lower.

Figure 5 *Land requirements of green methanol production. Please note the different scales of the y-axis. The diagrams show the same supply variants and energy supply scenarios as depicted in Figure 2. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, PEM - Proton exchange membrane.*

3.1.2.4. Water use
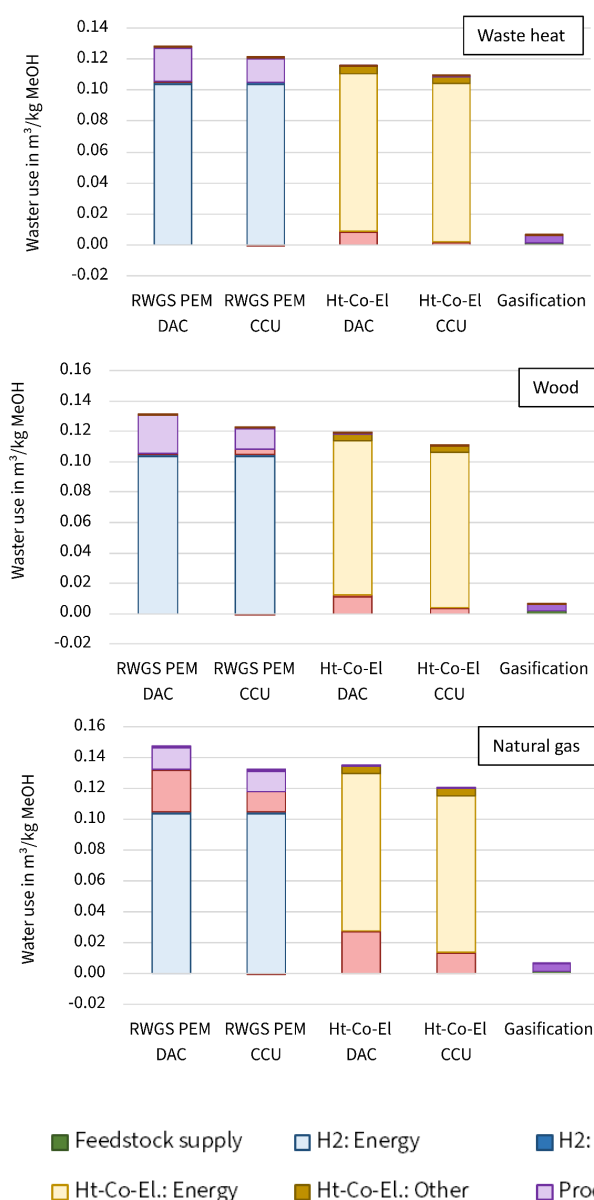
Like the other indicators, water use is mainly caused by the demand for electricity. There is only a minor difference between the different technical setups. There is also only a minor difference between the different heat supply variants.

In contrast, electricity supply has an impact on the water demand: if electricity is supplied by wind, the water demand of all set-ups ranges from 6 to 11 10^{-2} m^3 per kg methanol, whereas all other electricity supply variants range from 11 to 16 m^3 per kg methanol (section A.2 in the Annex).

Again, biomass gasification and subsequent methanol refining results in a comparably low impact.

Figure 6 *Water requirements of green methanol production. The diagrams show the same supply variants and energy supply scenarios as depicted in Figure 2. Abbr.: DAC - Direct air capture, GHG - Greenhouse gas, Ht-Co-El. - High-temperature co-electrolysis, MeOH - Methanol, PEM - Proton exchange membrane.*

## 3.2. Environmental impact of conventional heavy fuel oil and methanol

The environmental indicators of methanol and HFO production and combustion are listed in Table 1. Methanol is often used as a bulk chemical to synthesize other compounds. These compounds and materials will eventually be incinerated (or oxidized) at some point in the future.

Table 1 *Environmental indicator scores of substituted conventional HFO and methanol. All indicators are expressed per kg substituted HFO or conventional methanol. Please note: if fossil methanol is displaced in the shipping industry, green methanol displaces HFO according to the energetic content (and combustion efficiencies).*

Indicator	Unit	Heavy fuel oil		Conventional methanol	
		Production	Combustion	Production	Combustion
Abiotic resource depletion	10^{-6} kg Sb-eq./kg substituted	0.11		0.12	
Climate Change	kg CO_2-eq./kg substituted	0.30	3.17	0.85	1.38
Land use	m^2*a/kg substituted	0.02		0.01	
Fossil energy demand	MJ/kg substituted	47.33		38.44	
Water	10^{-3} m^3/kg substituted	15.11		22.51	

In this study, the environmental impact of conventional methanol production is taken from the Ecoinvent database (Wernet et al. 2016; Althaus et al. 2007). In the European market, natural gas is by far the most common feedstock used to produce methanol. The used reference values for GHG emissions is at the lower range of values reported in literature, especially if methanol is produced from coal (Figure A.1 in the Annex). The GHG emissions from conventional methanol production can be reduced by recycling CO_2 (Blumberg, Morosuk, and Tsatsaronis 2017). Such approaches might reduce GHG emissions of conventional methanol production. However, in the medium-term a complete termination of the use of fossil energy is needed to achieve climate targets and to end the dependency on these fossil resources.

3.3. Overall net change in environmental impacts

Based on the environmental indicators of methanol supply and the conventional counterparts that are likely to be substituted, the overall net change in environmental indicators resulting from a market entry of C1 can be determined. The net change in environmental indicator scores is listed in Table 2.

Table 2 *Net change in environmental indicator scores resulting from a potential displacement of conventional methanol or heavy fuel oil by green methanol. The presented values are the average, mean, minimum and maximum values of all energy supply scenarios and technical setups. A negative sign indicates a net improvement. The minimum refers to the mathematical minimum. Thus, in the case of a net reduction (negative sign), the minimum is the highest net reduction (being the lowest value).*

Indicator		Substitution	Average	Median	Min.	Max.
Climate Change	kg CO_2-eq./kg	Heavy fuel oil	-1.29	-1.45	-1.61	-0.52
		Conventional methanol	-1.82	-1.97	-2.13	-1.04
Abiotic resource depletion	10^{-6} kg Sb-eq./kg	Heavy fuel oil	20.88	18.63	3.04	49.91
		Conventional methanol	20.61	17.98	2.93	49.8
Fossil energy demand	MJ/kg	Heavy fuel oil	-16.78	-19.15	-21.56	-3.92
		Conventional methanol	-40.9	-43.28	-45.68	-28.05
Land demand	m^2*a/kg	Heavy fuel oil	0.35	0.06	-0.01	1.44
		Conventional methanol	0.34	0.05	-0.03	1.43
Water demand	10^{-3} m^3/kg	HFO	86.47	84.85	-1.26	154.28
		Conventional methanol	78.77	77.15	-8.96	146.58

The reference values used to assess the potential displacement effects are a rather conservative case (section 3.2 and Figure A.1 in the Annex). If the green methanol displaces conventional methanol made from coal, much higher net reductions in GHG emissions can be achieved.

This is in line with previous studies on so-called power-to-X technologies (PtX), cf. (Ausfelder and Dura 2019; Hannula and Reiner 2019; P. Schmidt et al. 2018). PtX-technologies use electricity, hydrogen and often a carbon source to provide substitutes for conventional, fossil-derived fuels and chemicals. **The stated literature shows that PtX fuels are performing much better than fossil counterparts in terms of GHG emissions. However, they exhibit a higher resource consumption.**

3.4. Sensitivity analysis: GHG intensity of the electricity supply

The previously presented results show that electricity supply is a major contributor to environmental impacts of all technological setups except for the biomass gasification route. Figure 7 shows the dependency of GHG emissions of C1's methanol provision on the GHG intensity of the electricity supply. The figure shows that using any source with a GHG intensity of below ~150 g CO_2-eq. per kWh will result in a net decrease in GHG emissions. Already today, several EU countries provide electricity with a GHG intensity lower than these 150 g CO_2-eq./kWh.
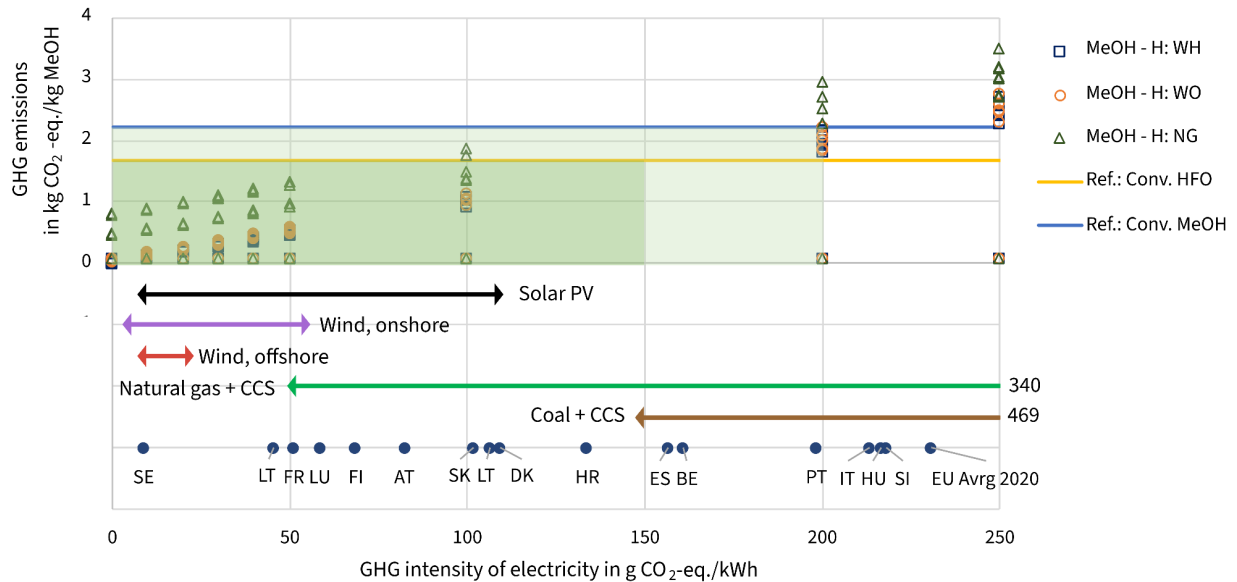
Figure 7 *Dependence of GHG emissions on the GHG intensity of electricity supply. The GHG intensity of electricity supply is shown on the x-axis. Depending on the location and technical characteristics, different electricity supply technologies result in a range of GHG emissions (United Nations 2021). The graph shows the ranges of solar PV, onshore and offshore wind turbines as well as natural gas and coal power plants using carbon capture and storage (CCS). In addition, the GHG intensity of different EU countrie's electricity supply is indicated by dark blue dots (country abbreviations according to ISO 2-digit country codes) (European Environmental Agency 2021). Please note: these values just serve as a reference because they present average GHG intensities, whereas ramping up C1's supply chain, including hydrogen supply by electrolysis, would trigger an increase in marginal electricity supply, which might differ considerably from the average electricity supply. The y-axis shows GHG emissions per kg methanol supply of all assessed technological setups and CO_2 supplies. Coloured symbols are used to represent different heat supply variants (excess waste heat (blue squares), wood chips (orange circles) and natural gas (green triangles)). The yellow and blue lines represent the displaced conventional HFO and methanol production and combustion/incineration. C1's methanol supply results in a net decrease in GHG emissions as long as the GHG emissions of methanol supply are below these lines (green shaded areas). Abbr.: country abbreviations according to ISO 2-digit country codes, CCS - Carbon capture and storage, GHG - Greenhouse gas, MeOH - Methanol, PV - Photovoltaics.*

3.5. Brief discussion of other alternatives to fossil heavy fuel oil

There are numerous alternatives to fossil fuels in the transportation sector (Ampah et al. 2021). Certain transportation modalities rely on fuels with high energy density. In the aviation and shipping industries for example there are only few alternatives in sight that could make liquid fuels obsolete within the timeframe needed to mitigate climate change in an effective and timely manner:

- **Biofuels:** A widely discussed alternative to fossil bunker oil is biofuels. There are numerous pathways to obtain fuels from all types of biomass, e.g. lignocellulose, sugars, fats and starch (Neuling and Kaltschmitt 2018). Biofuels made from crops that are dedicatedly grown for biofuel production require vast land areas and water resources (Buchspies and Kaltschmitt 2018). If land-use change (direct (dLUC) and indirect (iLUC)) are considered, GHG emissions could exceed

the GHG intensity of fossil. Biofuels are mostly cultivated on fertile land that could either be used for the production of food, feed and fiber or as a natural habitat. Scientific literature reports a range of 30 to 120 EJ of bioenergy potential globally (Roth, Riegel, and Batteiger V. 2018). This would be sufficient to provide a considerable amount of biofuels. A major drawback of many biofuel concepts is that often land is used for cultivation of (energy) crops. Increasing the demand for biofuels eventually results in the expansion of agricultural land entailing severe environmental and social risks, such as biodiversity loss and increase in staple food prices, cf. (Buchspies and Kaltschmitt 2018). Large-scale biofuel projects have been criticized for disrespecting land rights of local communities, too. Using biomass residues alleviates certain key pressures but a sustainable use of residues is unlikely to be able to serve the demand for alternative fuels alone.

- **Hydrogen:** Hydrogen can be used to propel electric engines and combustion engines. Using hydrogen in a combustion engine reduces the overall efficiency drastically. A main challenge of using hydrogen is the comparably low volumetric energy density resulting in high space requirements in ships. The additional space requires a re-design of ships and fuel supply infrastructure. Hydrogen supply will result in similar environmental impacts as the discussed methanol pathways. This is because a majority of the impact of the discussed methanol supply routes originates from hydrogen supply. Hence, using pure hydrogen will result in similar resource, water and land requirements.
- **Ammonia:** Ammonia has a much higher energy density than hydrogen. It is therefore more suitable as a fuel in marine ships. Again, alternative supply routes to provide ammonia require hydrogen and therefore electricity from renewable sources, resulting in a similar impact profile than the methanol assessed in this study. An advantage of ammonia is that it does not require any carbon source. On the other hand, handling and storage of ammonia is more challenging than other fuels that can be easily and safely handled and stored with existing infrastructure.
- **Liquefied natural gas (LNG):** LNG is a widely discussed alternative to conventional bunker oil. There are abundant resources available. However, due to its fossil origin, using LNG (without any CO_2 capturing) is not compatible with climate targets.

Ships have a long life-time making fleet replacement rates very slow. Hence, optimizing existing ships and their operation, e.g. by slow steaming and better routing, as well as replacing fuels used might be the fastest way to mitigate climate change. Alternatively, existing ships can be retrofitted to run on more sustainable fuels. Temporal aspects of technology ramp-up should therefore be taken into consideration when comparing different options to reduce the dependency on fossil energy sources. Methanol can be used as a 'drop-in' fuel in many applications and could therefore provide a timely reduction in GHG emissions.

3.6. Additional environmental considerations
Planet A's impact assessment framework focuses on the environmental indicators evaluated in this study, i.e. climate change and resource demand (abiotic resources, fossil energy resources, land and water) as well as waste (not specifically addressed in this study). In addition to these environmental indicators, using methanol as a fuel in the shipping industry might bring several other benefits. For instance, methanol reduces SO_x, NO_x and particulate matter emissions by 90 to 97, 30 to 50 and 90%, respectively (MAN Energy Solutions 2021). NO_x emissions can be driven further down by using a fuel mixture containing methanol, water and diesel (ibid.), making such a fuel mixture compliant with the International Maritime Organization (IMO) Tier III emission standard.

4. Limitations

There a several limitations that should be considered when interpreting the presented results:

- This study is an ex-ante assessment of technologies that have not reached a full market maturity yet. Whenever possible, first hand industry data was used. If such data was not available, publically available scientific literature and reports were the preferred source of information. For instance, the gasification route is largely based on published data of the GoBiGas project. Therefore, the gasification is based on year-long gathered experimental data. The data used for electrolyzers is mainly from scientific studies, of which some include first hand industry data. The data of the conversion step, operated by C1, is currently based on modeling data and experimental trials on catalyst efficiency. This implies that the future synthesis plants operated by C1 might operate under different conditions with differing technical specifications as assessed in this study. However, empirical data was used whenever available to reduce the uncertainty.

- The used background data (e.g. all material supplies) are modeled with currently available LCA databases and studies. However, in the next decades, the overall economy is likely to transform towards less fossil-based and towards more sustainable activities. Thus, the overall impact of materials used in the supply chain is likely to decrease in time. Such effects would further decrease the impact of green methanol production.

- There are several notable aspects regarding substitution:

  - Only one reference process was chosen. In reality, displaced technologies might change depending on when this displacement happens, in which market it happens and how much is displaced. For instance, the least profitable or least desired, e.g. because of regulatory or environmental aspects, conventional methanol might be pushed out of the market. Depending on the market and time of the displacement happening, the displaced conventional methanol or HFO might have a different environmental impact than the processes assessed in this study. For instance, this study assumes European market conditions where conventional methanol is mainly produced from natural gas. In contrast, methanol produced in China is mainly produced using coal. In such a case, the potential benefit of displacing fossil methanol is much higher.

  - A full substitution of conventional methanol and HFO was assumed. If green methanol is supplied, the price for conventional methanol or HFO might decrease. This might in turn increase the demand for methanol or HFO (price elasticity). However, for short-midterm, sustainably produced methanol will most likely target other markets where a price premium is being paid that allows the use of sustainable methanol. In the case of HFO, sustainable methanol could reduce the demand for conventional HFO resulting in the described feedback loop.

- In this study, energy and material requirements to retrofit ships are neglected because it is assumed that ships are replaced by methanol-fueled ships after their lifetime. As there is no data on methanol-fueled container ships available, it was assumed that switching to these types of ships occurs as it would have occurred without the ramp-up of C1. Hence, C1 will not result in a change of environmental impacts that would not have happened otherwise.

5. Conclusion

This LCA provides insight into the potential changes in environmental impacts arising from the ramp-up of C1's green methanol production. The results show that green methanol production is likely to decrease GHG emissions and the demand for fossil fuels. A wide range of scenarios and energy supply variants resulted in a **net decrease in GHG emissions ranging from 0.5 to 2.1 kg CO_2-eq. per kg methanol** and **a net decrease in fossil energy demand ranging from 4 to 46 MJ per kg methanol**. Energy supply is the most important contributor to green methanol production, if electrolysis is used (either to provide hydrogen or to provide synthesis gas via high temperature co-electrolysis). The supply of methanol eventually displaces conventional methanol or heavy fuel oil. These displacements cause the stated net reductions in GHG emissions and fossil energy demand. **In the other impact categories, green methanol is likely to result in an increase in indicator scores. This is a result that confirms previous scientific studies assessing the environmental implications of PtX technologies.** This clearly presents a trade-off that needs to be considered. In view of the urgent need to decarbonize the industry, alternatives are needed that can be deployed at large scale in a timely manner.

Depending on the carbon source and electricity used to produce green methanol, green methanol potentially qualifies as a 'renewable fuel of non-biological origin' according to the Renewable Energy Directive II (European Parliament and Council 2018). The latest proposal of the European Commission to revise the Renewable Energy Directive II includes mechanisms to promote the non-fuel use of 'renewable fuel of non-biological origin in other sectors, such as the chemical industry (European Commission 2021). The outcomes of this study indicate that C1's drop-in fuels and chemicals are one way to achieve a timely reduction of GHG emissions.

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Annex

A.1. Additional Life Cycle Inventory

A.1.1. LCI of electrolyzers

Table A.1 *LCI of a PEM stack (Delpierre et al. 2021). Several input materials are not available in the Ecoinvent Database. In such cases, the inventory supplied by (Delpierre et al. 2021) was used. The LCI of these processes can be found in (Delpierre et al. 2021).*

Material	Unit	Value	Comment
Steel, unalloyed	kg/kW	10	
Activated carbon, granular	kg/kW	45	
Aluminum, cast alloy	kg/kW	233	
Carbon fiber	kg/kW	$2.25\ 10^{-4}$	Modeled according to inventory supplied in (Delpierre et al. 2021)
Cast iron	kg/kW	0.12	
Platinum + Iridium	g/kW	0.08	Pt production was also used as a proxy for Ir production
Graphite	g/kW	03.06	
Titanium tetrachloride	g/kW	138.47	
Nafion	g/kW	2	Modeled according to inventory supplied in (Delpierre et al. 2021)
Copper	g/kW	9	
Oxygen, liquid	g/kW	8.23	
Silicon, metallurgical grade	kg/kW	$5.73\ 10^{-4}$	
Synthetic rubber	kg/kW	$9.78\ 10^{-5}$	

Table A.2 *LCI of AEL stack (Delpierre et al. 2021). Several input materials are not available in the Ecoinvent Database.*

Material	Unit	Value	Comment
Acetic anhydride	kg/kW	0.009	
Acrylonitrile-butadiene-styrene copolymer	kg/kW	0.0267	
Aluminum, cast alloy	kg/kW	0.075	
Aniline	kg/kW	0.0081	
Calendering, rigid sheets	kg/kW	0.13	
Carbon monoxide	kg/kW	0.025	
Chromium	kg/kW	0.163	
Copper, anode	kg/kW	0.33	
Electricity, high voltage	MJ/kW	6	
Graphite	kg/kW	0.0717	
Hydrochloric acid, without water, in 30% solution state	kg/kW	0.0217	
Industrial machine, heavy, unspecified	kg/kW	$2.67\ 10^{-5}$	
Lubricating oil	kg/kW	$8.05\ 10^{-5}$	
N-methyl-2-pyrrolidone	kg/kW	0.217	
Nickel, class 1	kg/kW	2	
Nitric acid, without water, in 50% solution state	kg/kW	0.0055	
Plaster mixing	kg/kW	0.13	
Polyphenylene sulfide	kg/kW	0.0567	
Polysulfone	kg/kW	0.0433	
Purified terephthalic acid	kg/kW	0.0147	
Steel, unalloyed	kg/kW	30	
Tetrafluoroethylene	kg/kW	0.013	
Water, decarbonised	kg/kW	1.83	
Water, deionised	kg/kW	14.3	
zirconium oxide	kg/kW	0.183	

Table A.3 *LCI of SOEC stack (Häfele, Hauck, and Dailly 2016). Several input materials are not available in the Ecoinvent Database. In such cases, proxies were used as indicated in the comment section.*

Material	Unit	Value	Comment
Cerium oxide	kg/kW	0.262	Proxy for Yttriadoped Ceria (YDC)
Electricity, high voltage	kWh/kW	49.8	
Glass fiber	kg/kW	0.059	Proxy for Glass sealant paste
Lanthanum oxide	kg/kW	0.425	Proxy for Yttria Stabilized Zirconia (YSZ)
Lanthanum-cerium oxide	kg/kW	0.038	proxy for LSCF and LSCo
Manganese concentrate	kg/kW	0.004	
Nickel, class 1	kg/kW	1.009	proxy for Ni/YSZ
Steel, chromium steel 18/8	kg/kW	0.020563	

A.1.2. LCI of CO2 supply

Table A.4 *LCI of a DAC unit (Schreiber et al. 2020).*

Material	Unit	Value	Comment
Aluminum, primary, ingot	t	2.096	
Concrete, normal	m^3	1	
Copper, anode	t	1.7	
Ethylene glycol	t	15	
Gravel, crushed	t	93.1	
Sand	t	89.6	
Silicone product	t	1.1	
Steel, chromium steel 18/8, hot rolled	t	3.63	
Steel, low-alloyed	t	3.03	
Stone wool	t	8.7	
Wire drawing, copper	t	1.7	

Table A.5 *LCI of a CO_2 capturing from flue gas (Giordano, Roizard, and Favre 2018).*

	Material	Unit	Value	Comment
In	Activated carbon, granular	kg	$7.00\ 10^{-2}$	
	Electricity	kWh	98.3	
	Heat	GJ	3.2	
	Monoethanolamine	kg	1.44	
	Sodium hydroxide, without water, in 50% solution state	kg	0.12	
	Tap water	kg	18.1	
Out	Acetaldehyde	kg	$1.50\ 10^{-4}$	
	Ammonia	kg	0.03	
	Argon-40	kg	54.8	
	Carbon dioxide (captured)	kg	1000	
	Formaldehyde	kg	$2.40\ 10^{-4}$	
	hazardous waste, for incineration	kg	2.9	
	Monoethanolamine	kg	$6.00\ 10^{-4}$	
	Nitrogen	kg	3202.2	
	Spent activated carbon, granular	kg	0.07	
	Water	m³	$8.75\ 10^{-2}$	

A.1.3. LCI of synthesis gas production

Table A.6 *LCI of the rWGS reactor (Sternberg and Bardow 2016).*

	Material	Unit	Value	Comment
In	CO_2	kg	1.581	
	Hydrogen	kg	0.072	
	Electricity	kWhg	1.34	
	Heat	kWh	0.61	
	Synthetic gas factory	units	$2.00\ 10^{-9}$	
Out	Carbon monoxide	kg	1	
	Wastewater, unpolluted	m³	$6.43\ 10^{-4}$	

Table A.7 LCI of the high temperature co-electrolysis cell (Schreiber et al. 2020).

	Material	Unit	Value	Comment
In	Benzyl alcohol	g	3.01	
	Carboxymethyl cellulose, powder	g	3.01	
	Cerium oxide	g	0.201	
	Cobalt hydroxide	g	0.394	
	Copper oxide	g	0.143	
	Electricity, medium voltage	kWh	0.12	
	Ethanol, without water, in 99.7% solution state, from fermentation	g	7.62	
	Ethylene, average	g	7.62	
	Lanthanum oxide	g	1.98	
	Manganese dioxide	g	0.351	
	Methyl ethyl ketone	g	7.62	
	Nickel, class 1	g	17.9	
	Nitric acid, without water, in 50% solution state	g	8.73	
	Samarium-europium-gadolinium oxide	g	0.053	
	Strontium carbonate	g	0.324	
Out	Ht - Co- Electrolysis Cell	units	1	
	Inert waste, for final disposal	g	38.6	
	Nitrogen oxides	g	0.32	
	Non-methane volatile organic compounds, unspecified origin	g	6.38	

Table A.8 LCI of the high temperature co-electrolysis of a single stack (Schreiber et al. 2020).

Material	Unit	Value	Comment
Cast iron	kg	414	
Chromium	kg	117	
Cobalt	kg	1.5	
Electricity, low voltage	kWh	3611.5	
Glass cement	kg	19.9	Table A.10
Heat, from steam, in chemical industry	kWh	606	
Lanthanum oxide	kg	0.483	
Manganese	kg	2.84	
Nickel, class 1	kg	19.8	
Sheet rolling, chromium steel	kg	534	
Titanium, primary	kg	0.374	

Table A.9 *LCI of the high temperature co-electrolysis of the Ht-Co-Electrolysis plant (Schreiber et al. 2020).*

	Material	Unit	Value	Comment
In	Building, hall, steel construction	m^2	0.672	
	Building, multi-storey	m^3	4.08	
	Construction work, heat and power cogeneration unit, 160kW electrical	Item(s)	4.2	
	Electricity, low voltage	kWh	1440	
	Electricity, medium voltage	kWh	7242	
	Heat, district or industrial, other than natural gas	kWh	3000	
	Heat, from steam, in chemical industry	kWh	3535	
	Inverter, 500kW	Item(s)	0.3	
	Sheet rolling, chromium steel	kg	1875	
	Steel, chromium steel 18/8	kg	1875	
	Tap water	kg	4086	
Out	Ht-Co-Electrolysis Plant	units	1	
	Wastewater, unpolluted	m^3	4.09	

Table A.10 *LCI of glass cement production (Schreiber et al. 2020).*

	Material	Unit	Value	Comment
In	Boric oxide	kg	25.6	
	Carbon black	kg	24.3	
	Chemical, organic	kg	10	
	Chromium oxide, flakes	kg	25.6	
	Electricity, low voltage	kWh	1610	
	Ethylene glycol	kg	12.6	
	Fatty acid	kg	12.6	
	Quicklime, milled, packed	kg	39.2	
	Silica sand	kg	192	
	Vinyl acetate	kg	226	
	Yttrium oxide	kg	13.4	
	Zinc oxide	kg	25.6	
	Zirconium oxide	kg	82.5	
Out	Glass cement	kg	1000	
	Carbon monoxide, to air	kg	113	
	Non-methane volatile organic compounds, to air	kg	193	

Table A.11 LCI of biomass gasification based on data reported from the GoBiGas project (Ahlström et al. 2019; Alamia et al. 2017; Larsson, Gunnarsson, and Tengberg 2018; Thunman et al. 2018).

	Material	Unit	Value	Comment
In	Activated carbon, granular	kg	$9.15 \cdot 10^{-4}$	
	C1 Catalyst used for 1 t MeOH	kg	$1.00 \cdot 10^{-3}$	
	Emissions from syngas production	Item(s)	4.01	
	Industrial furnace, natural gas	Item(s)	$2.00 \cdot 10^{-9}$	
	Nitrogen, liquid	kg	$1.36 \cdot 10^{-3}$	
	Olivine, milled	kg	$2.20 \cdot 10^{-2}$	
	Potassium carbonate	kg	$3.55 \cdot 10^{-4}$	
	Quicklime, milled, loose	kg	$4.07 \cdot 10^{-2}$	
	Synthetic gas factory	Item(s)	$2.00 \cdot 10^{-9}$	
	Tap water	kg	$1.36 \cdot 10^{-3}$	
	Vegetable oil methyl ester	kg	$2.37 \cdot 10^{-42}$	
	Wood chips, wet	kg	4.00	
Out	Fly ash and scrubber sludge	kg	$1.19 \cdot 10^{-2}$	
	Methanol	kg	1	
	Spent activated carbon, granular	kg	$9.15 \cdot 10^{-4}$	
	Wastewater, average	m^3	$1.36 \cdot 10^{-6}$	
	Wood ash mixture, pure	kg	$5.09 \cdot 10^{-2}$	
	Emissions, to air			Emissions taken from Ecoinvent process emissions from synthetic gas production, from wood, at fluidized bed gasifier | synthetic gas

A.2. Additional results

Table A.12 Results of all assessed technologies and energy scenarios. All results refer to the production of 1 kg of methanol. The table continues on the next page.

		95%-Reduction scenario			Wind onshore			Wind offshore			Solar PV		
		WH	Wood	NG	WH	Wood	NG	WH	Wood	NG	WH	Wood	NG
Climate Change	RWGS PEM DAC	0.41	0.47	1.18	0.15	0.21	0.47	0.17	0.22	0.94	0.24	0.3	1.02
kg CO_2-eq./kg	RWGS PEM flue gas	0.38	0.42	0.84	0.14	0.17	0.42	0.15	0.18	0.61	0.22	0.26	0.68
	RWGS AEL DAC	0.41	0.47	1.18	0.15	0.21	0.47	0.16	0.22	0.94	0.24	0.3	1.02
	RWGS AEL flue gas	0.38	0.41	0.84	0.13	0.17	0.41	0.15	0.18	0.61	0.22	0.26	0.68
	RWGS SOEC DAC	0.37	0.42	1.14	0.13	0.19	0.42	0.15	0.2	0.92	0.22	0.27	0.99
	RWGS SOEC flue gas	0.34	0.37	0.8	0.12	0.15	0.37	0.13	0.16	0.59	0.2	0.23	0.66
	Ht-Co-El DAC	0.39	0.44	1.16	0.16	0.22	0.44	0.17	0.23	0.94	0.24	0.3	1.01
	Ht-Co-El flue gas	0.36	0.39	0.82	0.14	0.18	0.39	0.16	0.19	0.61	0.22	0.25	0.68
	Gasification	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Abiotic depletion	RWGS PEM DAC	29.53	29.92	30.04	20.19	20.58	29.92	23.54	23.93	24.06	49.51	49.9	50.02
10^{-6} kg Sb-eq./kg	RWGS PEM flue gas	18.74	18.97	19.05	9.88	10.11	18.97	13.06	13.29	13.37	37.69	37.93	38
	RWGS AEL DAC	22.73	23.12	23.24	13.39	13.78	23.12	16.74	17.14	17.26	42.71	43.1	43.22
	RWGS AEL flue gas	16.42	16.65	16.72	7.56	7.79	16.65	10.74	10.97	11.05	35.37	35.6	35.68
	RWGS SOEC DAC	20.16	20.55	20.68	11.79	12.18	20.55	14.79	15.19	15.31	38.07	38.47	38.59
	RWGS SOEC flue gas	14.38	14.62	14.69	6.49	6.72	14.62	9.32	9.56	9.63	31.27	31.5	31.57
	Ht-Co-El DAC	28.18	28.57	28.69	19.96	20.35	28.57	22.92	23.31	23.43	45.75	46.14	46.26
	Ht-Co-El flue gas	22.31	22.54	22.62	14.58	14.81	22.54	17.36	17.59	17.66	38.86	39.09	39.16
	Gasification	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56	4.56

Table A.12 continued *Results of all assessed technologies and energy scenarios. All results refer to the production of 1 kg of methanol.*

|		95%-Reduction scenario			Wind onshore			Wind offshore			Solar PV		
		WH	Wood	NG	WH	Wood	NG	WH	Wood	NG	WH	Wood	NG
CED	RWGS PEM DAC	7.26	7.96	19.29	2.15	2.85	7.96	2.35	3.05	14.38	4.04	4.74	16.07
MJ/kg	RWGS PEM flue gas	6.74	7.15	13.87	1.9	2.31	7.15	2.09	2.5	9.21	3.69	4.1	10.82
	RWGS AEL DAC	7.24	7.94	19.26	2.13	2.83	7.94	2.33	3.03	14.36	4.02	4.72	16.05
	RWGS AEL flue gas	6.71	7.12	13.84	1.86	2.28	7.12	2.05	2.47	9.18	3.66	4.07	10.78
	RWGS SOEC DAC	6.5	7.19	18.52	1.92	2.62	7.19	2.1	2.8	14.12	3.61	4.31	15.64
	RWGS SOEC flue gas	5.97	6.38	13.1	1.65	2.07	6.38	1.82	2.24	8.95	3.25	3.67	10.38
	Ht-Co-El DAC	6.72	7.42	18.72	2.23	2.93	7.42	2.41	3.1	14.4	3.89	4.59	15.89
	Ht-Co-El flue gas	6.19	6.61	13.3	1.96	2.38	6.61	2.13	2.54	9.24	3.53	3.94	10.64
	Gasification	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82	1.82
Land use	RWGS PEM DAC	0.04	1.37	0.1	0.01	1.34	1.37	0.01	1.34	0.07	0.12	1.45	0.17
m^2*a/kg	RWGS PEM flue gas	0.04	0.83	0.07	0.01	0.8	0.83	0.01	0.8	0.04	0.11	0.9	0.14
	RWGS AEL DAC	0.04	1.37	0.1	0.01	1.34	1.37	0.01	1.34	0.06	0.12	1.45	0.17
	RWGS AEL flue gas	0.04	0.83	0.07	0	0.79	0.83	0.01	0.8	0.04	0.11	0.9	0.14
	RWGS SOEC DAC	0.03	1.37	0.09	0	1.34	1.37	0.01	1.34	0.06	0.1	1.44	0.16
	RWGS SOEC flue gas	0.03	0.82	0.06	0	0.79	0.82	0	0.8	0.04	0.1	0.89	0.13
	Ht-Co-El DAC	0.04	1.37	0.1	0.01	1.34	1.37	0.01	1.34	0.07	0.11	1.44	0.16
	Ht-Co-El flue gas	0.04	0.82	0.07	0.01	0.8	0.82	0.01	0.8	0.04	0.1	0.89	0.13
	Gasification	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Water	RWGS PEM DAC	127.65	130.94	146.92	84	87.28	130.94	75.17	78.46	94.45	142.42	145.71	161.69
10^{-3} m^3/kg	RWGS PEM flue gas	120.23	122.18	131.65	78.82	80.77	122.18	70.45	72.4	81.87	134.24	136.19	145.66
	RWGS AEL DAC	127.49	129.44	146.77	83.84	87.13	129.44	75.02	78.31	94.29	142.26	145.55	161.54
	RWGS AEL flue gas	119.96	121.91	131.38	78.55	80.5	121.91	70.18	72.13	81.6	133.97	135.92	145.4
	RWGS SOEC DAC	114.14	117.43	133.42	75	78.29	117.43	67.09	70.38	86.36	127.39	130.67	146.66
	RWGS SOEC flue gas	106.7	108.64	118.12	69.8	71.74	108.64	62.34	64.29	73.76	119.18	121.13	130.6
	Ht-Co-El DAC	115.5	118.78	134.72	77.11	80.39	118.78	69.35	72.63	88.58	128.49	131.76	147.71
	Ht-Co-El flue gas	108.8	110.74	120.19	72.65	74.59	110.74	65.34	67.28	76.73	121.03	122.98	132.43
	Gasification	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15
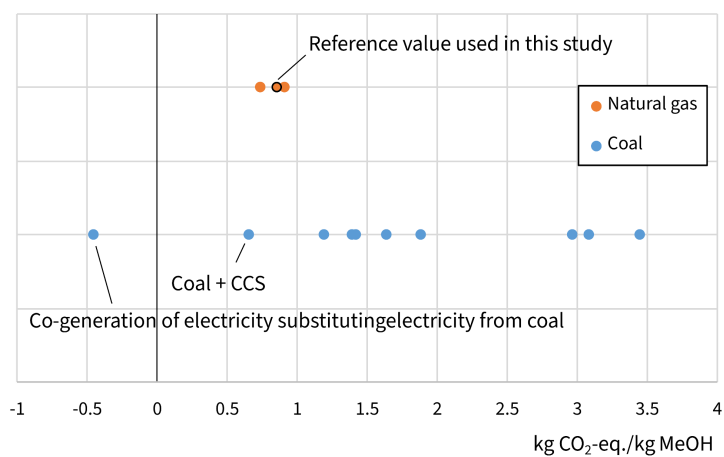
Figure A.1 *Comparison of GHG emissions of conventional methanol production from natural gas and coal. Values taken from (Śliwińska, Burchart-Korol, and Smoliński 2017; J. Li et al. 2018; H. Li, Yang, and Qian 2012; Z. Li et al. 2010; Qin et al. 2016)*

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