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Climate and environmental effects of the manufacture of PtGLS products and technical measures for mitigation

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Abstract: Climate and environmental effects of the manufacture of PtGLS products and technical measures for mitigation (NEET), Work Package 3 "Environmental impacts of the provision of electricity-based energy carriers"

The aim of Work Package 3 in the research project "NEET – Criteria for the sustainable provision and climate-friendly integration of electricity-based renewable energy carriers" is to comprehensively assess the environmental impacts of synthetic energy carriers (PtGLS: Power to Gas, Liquids, Solids) and to identify options for action for the environmentally friendly design of these technologies. The focus is on analyzing how PtGLS products such as hydrogen, methane, methanol, ammonia, or liquid fuels can be integrated into a climate-neutral energy system in an ecologically sustainable way.

The chosen methodological approach is based on life cycle assessments (LCA) for 56 detailed modeled supply paths. These cover the entire process chain – from electricity supply via synthesis and derivatization to transport and reconversion. In addition, measures to reduce environmental impacts were derived and their mitigation potential analyzed in twelve target scenarios.

The results show that PtGLS products enable significant reductions in climate impact compared to fossil references in many cases – especially when using fully renewable electricity. For methanol, dimethyl ether (DME), ammonia, and Fischer-Tropsch fuels (FT), greenhouse gas emissions can be reduced by up to 80%, while synthetic methane enables a reduction of around 60%. The choice of electricity source is crucial: wind power has the lowest climate impact, while the use of grid electricity can negate all climate benefits.

At the same time, in other environmental categories – such as acidification, eutrophication, particulate matter, resource consumption, and land use – there are in many cases higher impacts compared to fossil fuel-based products. This is due, among other things, to emissions from transport, infrastructure, chemical precursors, and high electricity and material requirements.

The study identifies specific mitigation measures for these environmental impacts, including the consistent use of renewable electricity, exhaust gas aftertreatment in ammonia processes, alternative membrane materials, and the use of seawater desalination to conserve freshwater resources. In addition, it highlights areas for action and conflicting goals that are important for future regulations and certification systems.

The study thus provides a sound basis for the ecological assessment and management of synthetic energy sources on the path to a climate-neutral energy supply.

Kurzbeschreibung: Klima- und Umwelteffekte der Herstellung von PtGLS-Produkten und technische Maßnahmen zur Minderung (NEET), Arbeitspaket 3 „Umweltwirkungen der Bereitstellung von strombasierten Energieträgern"

Ziel des Arbeitspakets 3 im Forschungsvorhaben „NEET – Kriterien für eine nachhaltige Bereitstellung und klimagerechte Integration von strombasierten erneuerbaren Energieträgern" ist es, die Umweltwirkungen synthetischer Energieträger (PtGLS: Power to Gas, Liquids, Solids) umfassend zu bewerten und Handlungsoptionen zur umweltgerechten Ausgestaltung dieser Technologien aufzuzeigen. Im Mittelpunkt steht die Analyse, wie PtGLS-Produkte wie Wasserstoff, Methan, Methanol, Ammoniak oder flüssige Kraftstoffe ökologisch tragfähig und langfristig in ein klimaneutrales Energiesystem eingebettet werden können.

Der gewählte methodische Ansatz basiert auf Ökobilanzen (Life Cycle Assessment, LCA) für 56 detailliert modellierte Bereitstellungspfade. Diese decken die gesamte Prozesskette ab – von der Strombereitstellung über die Synthese und Derivatisierung bis hin zu Transport und

Rückumwandlung. Ergänzend wurden Maßnahmen zur Reduktion der Umweltwirkungen abgeleitet und in zwölf Zielszenarien deren Minderungspotential analysiert.

Die Ergebnisse zeigen, dass PtGLS-Produkte in Bezug auf die Klimawirkung in vielen Fällen deutliche Entlastungen gegenüber fossilen Referenzen ermöglichen – insbesondere bei der Verwendung von vollständig regenerativem Strom. Für Methanol, dimethyl ether (DME), Ammoniak und Fischer-Tropsch-Kraftstoffe können bis zu 80 % weniger Treibhausgasemissionen erreicht werden, synthetisches Methan ermöglicht eine Reduktion um rund 60 %. Die Wahl der Stromquelle ist dabei entscheidend: Windstrom weist die niedrigsten Klimabelastungen auf, während die Nutzung von Netzstrom („Graustrom“) alle Klimavorteile zunichtemachen kann.

Gleichzeitig zeigen sich in anderen Umweltkategorien – etwa Versauerung, Eutrophierung, Feinstaub, Ressourcen- oder Flächenverbrauch – in vielen Fällen höhere Belastungen gegenüber fossilen Vergleichsprodukten. Ursache sind unter anderem Emissionen aus Transport, Infrastruktur, chemischen Vorprodukten und dem hohen Strom- und Materialbedarf.

Die Studie identifiziert konkrete Minderungsmaßnahmen für diese Umweltwirkungen, u. a. die durchgängige Nutzung von erneuerbarem Strom, Abgasnachbehandlung bei Ammoniakprozessen, alternative Membranmaterialien sowie den Einsatz von Meerwasserentsalzung zur Schonung von Süßwasserressourcen. Zusätzlich werden Handlungsspielräume und Zielkonflikte aufgezeigt, die für zukünftige Regelwerke und Zertifizierungssysteme von Bedeutung sind.

Die Untersuchung liefert damit fundierte Grundlagen für eine ökologische Bewertung und Steuerung synthetischer Energieträger auf dem Weg zu einer klimaneutralen Energieversorgung.

Table of content

List of figures

List of tables

List of abbreviations

Abbreviation	Explanation
AWARE	Available Water Remaining
AE	Country code United Arab Emirates
AEL	Alkaline electrolysis
ATR	Autothermal reforming of methane
AU	Country code for Australia
BAT	Best Available Techniques
BImSchG	Bundes Immissionsschutz Gesetz (Federal Immission Control Act)
BOG	Boil-off gas
CA	Country code for Canada
CCS	CO_2 capture with subsequent storage (Carbon Capture and Storage)
CF	carbon footprint
CL	Country code Chile
CSP	Concentrated solar power plants
DAC	CO_2 capture from the ambient air (Direct Air Capture)
DE	Country code for Germany
DEA	Diethanolamine
DK	Country code for Denmark
DME	Dimethyl ether
EoL	End-of-life stage (waste, disposal, recycling)
Eq.	Equivalents in the units of the aggregated environmental impact categories
ES	Country code for Spain
EU	European Union
FT	Fischer-Tropsch, polymerisation process for the production of hydrocarbons
GH_2	Gaseous Hydrogen
GHG	Greenhouse gas(es)
GWP	Global warming potential
h	Hour(s)
HHV	Higher heating value, formerly: upper heating value
HTE	High-temperature electrolysis
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change

Abbreviation	Explanation
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LDAR	Leak Detection and Repair
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MA	Country code for Morocco
MDEA	Methyl diethanolamine
MEA	Ethanol Amine
MENA	Region Middle East North Africa
MeOH	Methanol
MJ	Megajoule
MtG	Methanol-to-Gasoline
MW	Megawatt
NMVOC	Non-methane volatile organic compounds
PEI	Polyethyleneimine
PEMEL	Polymer electrolyte membrane electrolysis
PFAS	Per- and polyfluoroalkyl substances
PFOS	Perfluorooctanesulfonic acid
PTFE	Polytetrafluoroethylene
PtG	Power-to-Gas
PtGLS / PtX	Power-to-Gas/Liquid/Solid or Power-to-X
PV	Photovoltaics
QA	Country code for Qatar
RE	Renewable energies
RFNBO	Renewable Fuels of Non-Biological Origin
RWGS	Reverse water-gas shift reaction
SCR	Selective Calaytic Reduction
SMR	Steam methane reforming
SNG	Synthetic Natural Gas (methane)
SOEC	Solid oxide electrolysis cell
TRL	Technology readiness level

Abbreviation	Explanation
UBA	German Environment Agency (Umweltbundesamt)
US	Country code for USA
VOC	Volatile organic compounds
VRF	Vanadium redox flow battery
WIP	Waste Incineration plant

Note: Abbreviations for environmental impact categories are listed separately in Section 4.1.4.

Summary

The research project *Criteria for the sustainable provision and climate-friendly integration of electricity-based renewable energy sources,* or NEET for short, is investigating how PtGLS (Power to Gas, Liquids, Solids) products can be produced in an ecologically and socio-economically sustainable manner.

This short paper contains the results of work package 3, which aims to determine the environmental impacts of various processes and process paths for the production of PtGLS products using life cycle assessments (LCA) and to derive technical measures to limit the environmental effects. The following products are the focus of this study:

- Hydrogen (green, blue, turquoise)
- Ammonia (green, blue)
- Methane (green)
- Methanol (green)
- Dimethyl ether (green)
- Petrol/diesel/kerosene/naphtha (green)

Section 2 lists the individual processes that build the pathways to be investigated for the manufacture of these products. They are described as individual data sets with the most important parameters. A detailed description of the individual processes is provided in the separate technical appendix in the form of an Excel table. All energy and material flows for each process are described there.

Based on findings from previous studies, a "base case" is defined for each product in section 3. In addition, variations of the base cases are conducted, investigating the influence of parameters such as power source, transport medium and location.

The environmental impacts of the PtGLS paths examined are presented in section 4. First, the methodological basis for the calculation is described (section 4.1), followed by the results in the individual impact categories (section 4.3).

Section 5 identifies opportunities to reduce the most significant environmental impacts and quantifies the mitigation effects.

Investigated processes

- In general, PtGLS products are produced using renewable energy sources (RE). This study considers wind turbines, ground-mounted photovoltaic systems and concentrated solar power plants. Country- and region-specific renewable electricity mixes and grid electricity mixes are used for modelling.
- "Green" hydrogen is produced using electrolysis plants. The modelling covers both alkaline electrolysis (AEL) and polymer electrolyte membrane electrolysis (PEMEL). The energy and water requirements and the effects of polyfluorinated membranes and their alternatives are examined in detail.
- For "blue" hydrogen, methane reforming and subsequent CO_2 separation (carbon capture and storage, CCS) are modelled. Two processes are commonly used on an industrial scale to

produce hydrogen from natural gas/methane: steam methane reforming (SMR) and autothermal reforming (ATR).

- "Turquoise" hydrogen is produced by methane pyrolysis. Thermal pyrolysis converts methane into hydrogen and solid carbon.
- For carbon-based PtGLS products, CO_2 is extracted from the air using direct air capture (DAC) and then processed with hydrogen to produce the respective products. Other CO_2 sources considered are cement plants, waste incineration plants and biogas plants.
- Ammonia is one of the target products considered, as well as a transport derivative for hydrogen. The Haber-Bosch process is considered for ammonia synthesis; if hydrogen is to be recovered, ammonia cracking is used.
- Methane or synthetic natural gas (SNG) is produced from hydrogen and CO_2. The synthesis of methanol follows the same principal. In a further process step, dimethyl ether (DME) and fuels can be produced from methanol using the methanol-to-gasoline process. The production of fuels using the Fischer-Tropsch process is considered as well.
- The construction and dismantling of the plants for the production of PtGLS products are taken into account in the environmental impact assessment, as well as the used catalysts. The material requirements are accounted over the total quantity of product manufactured over the lifetime of the plant.
- Various transport options are available. These include, for example, the transport of liquid derivatives using conventional tankers and trucks, the transport of hydrogen and SNG via pipeline. Depending on the country of origin, various short- and long-distance transport options are modelled.

Process chains for the production of PtGLS products

From the various possibilities for combining the processes, life cycle assessments were calculated for a total of 56 paths for the production of PtGLS products. The process chains include the provision of raw materials and electricity/heat, the synthesis of hydrogen, conversion into derivatives if necessary, transport to Germany and, if necessary, reconversion to hydrogen. Based on the 56 pathways, six were defined as base cases and 50 were supplemented as variations with changes to individual process steps. Twelve further “target scenarios” were defined and calculated for the implementation of measures in the (near) future to reduce environmental impacts.

Climate and environmental effects of PtGLS products

The analysis of the life cycle assessment calculations shows which factors significantly influence the environmental impact of the provision of synthetic energy sources based on renewable energies. It also identifies potential conflicts between different impact categories – for example, when low greenhouse gas emissions are accompanied by higher environmental impacts in other areas. The focus lies on the LCA of climate impacts of PtGLS products and their extent to offer environmental benefits compared to fossil reference products.

- For **ammonia, methanol, DME and Fischer-Tropsch fuels,** a r**eduction in climate impact of around 80%** can be achieved in the base cases considered. For **synthetic natural gas**, a **reduction of 60%** is possible. For hydrogen shipped in the transport medium ammonia, the climate impact can be **reduced by around 50%** – if renewable electricity is also used in ammonia synthesis.

- The use of **grid electricity** that usually also contains significant proportions from non-renewable sources, **worsens the climate balance** in all process steps. This applies in particular to its use in electrolysis, but also in the synthesis, liquefaction or splitting of the transport medium and in the power supply of pipeline compressors.
- Since renewable electricity accounts for between 40 and 60% of the climate impact in most base cases, the **choice of renewable electricity source** has a significant influence on the overall result. **Wind power** is the source with the **lowest climate impact** and also shows only small absolute differences per kWh between different locations. The results for electricity from **photovoltaics** show **greater differences between locations,** but even in the most favourable case are **two to three times higher than those for wind power.**
- For the **hydrogen transport options** examined, import via **pipeline** has **the lowest climate impact**. Transport using **LOHC and DME** as transport media is **significantly higher.** If **ammonia** is used as the transport medium, it can compete with the results of **pipeline transport**, but only if **renewable electricity** is used **for NH_3-synthesis**. Otherwise, the climate impact is twice as high as that of pipeline transport.
- **Importing "blue" and "turquoise" hydrogen** using ammonia as a transport medium results in a climate impact that **is hardly better or even worse than the fossil reference.** The main reasons are greenhouse gas emissions in natural gas supply (especially methane) and CO_2 emissions in reforming. Using the technology examined here, the production of "turquoise" hydrogen leads to worse results than those of "blue" hydrogen.
- The **production of "blue" hydrogen in Germany**, on the other hand, could **reduce** the climate impact by **40–70%** compared to conventional production (reference). The prerequisite for the greatest possible reduction is the **import of natural gas with low upstream emissions** and the use of a process with **the highest possible CO_2 capture rate**. The volume required for CO_2 storage (CCS) as well as possible CO_2 leakages and losses from storage are not included.
- The choice between the AEL and PEMEL **electrolysis technologies** examined gives only **small differences.**
- There are **no major differences** between the production of renewable **ammonia** in **the examined countries** and in **Germany**, as the advantages of electricity generation are almost offset by the disadvantages of transport distances.
- **Transport** plays a significant role for **synthetic methane**. As with hydrogen, transport by **pipeline** is **the option with the lowest impact** for distances of up to 3,000–4,000 km. Liquefied **transport by ship** is **more advantageous** for **longer distances**, but generally negates the advantages of higher full-load hours for renewable energies in distant countries.
- For the liquid energy carriers **methanol, DME and Fischer-Tropsch fuel**, the **climate impact of the renewable electricity used** plays a greater role because the demand for hydrogen is high. **Transport by ship contributes less** than gaseous energy carriers.
- The climate impact of supplying petrol via the methanol-to-gasoline route is around **25% higher than that of the Fischer-Tropsch route, but still 70% lower than the fossil fuel reference.**

In contrast to the carbon footprint, most PtGLS pathways show **a significantly higher environmental impact** in all **other impact categories compared** to the respective fossil reference:

- In the "acidification" category, pathways involving the use of **ammonia** perform **particularly poorly**. However, the provision of **synthetic natural gas** and the liquid energy carriers **methanol, DME and Fischer-Tropsch fuels** also perform significantly **worse than the fossil reference**. This is mainly due to emissions of sulphur dioxide, nitrogen oxides and ammonia in background processes (infrastructure and transport).
- The provision of synthetic energy carriers leads to a significant increase in **eutrophication (overfertilising) compared to fossil references**. Eutrophication is also largely caused by emissions of ammonia and nitrogen oxides, additionally, phosphate emissions into water are considered– the latter when fossil grid electricity is used for transport processes.
- Only **methanol and DME** are **slightly better** than their fossil references in terms of **ozone depletion potential**. The base cases for hydrogen and ammonia are higher. **Fischer-Tropsch fuels are many times more harmful to the ozone layer** than fossil diesel. This is due to the manufacture of electrolysers, in which tetrafluoroethylene is used in the production of the membrane.
- The potential for **summer smog** formation is significantly **lower** for **ammonia, methanol, DME and Fischer-Tropsch fuels than for the respective fossil fuels**. However, the provision of **synthetic natural gas and hydrogen** via the transport medium ammonia is **many times worse**. In all cases, this is due to nitrogen oxide emissions in background processes (transport, infrastructure).
- **Particulate matter emissions** are potentially **significantly higher for all products than those of the respective fossil references.** For all synthetic products, nitrogen oxide emissions from infrastructure and transport processes contribute significantly. If grid electricity is used, SO_2 emissions are added. Supply paths using ammonia lead to high particulate matter potential via NH_3 emissions.
- The **cumulative energy consumption** for almost all synthetic products is **equal to or higher than that of the respective fossil reference.** Only **ammonia and methanol** require **slightly less energy input** in this comparison. In all cases, the electricity input for electrolysis is decisive.
- **The land area required** for renewable electricity generation is the reason why the **land use (hemeroby concept)** for synthetic products is **around 20–30 times higher** than that of fossil reference products.
- **Water demand** arises primarily in the background system, particularly from **fossil fuel power plants and infrastructure**. In the foreground system, **cooling water demand for electrolysis dominates,** while **freshwater demand for electrolysis** is **low** in comparison. Nevertheless, the latter should not be neglected, as the cooling water leaves the plant, while the water for electrolysis is permanently extracted from the local system.
- All base cases also show a **significant increase** in the **abiotic resource depletion potential for minerals and metals** in relation to the respective fossil reference. This is due to the demand for the construction of power generation and synthesis plants.

Options for reducing environmental impacts

Measures to further reduce environmental impacts were derived from the identified environmental impacts. Overall, they lead to an improvement in the environmental balance in most cases; only isolated minor conflicts of objectives arise. The most important measures and their effects are:

- The **renewable power supply** for all processes along the value chain (ATR/SMR, NH_3 synthesis, NH_3 and LOHC cracking, gas pipeline transport, etc.), including heat supply, is important for reducing the climate impact. The energy transition is a basic prerequisite for ensuring that, in addition to electrolysis, all other processes can also be powered by renewable electricity.
  - In particular, supplying derivative synthesis and, where applicable, its reconversion with renewable electricity instead of grid electricity and fossil heat leads to major improvements in the categories of climate change, acidification and eutrophication.
  - The operation of gas transmission and distribution networks with renewable electricity also leads to improvements, especially if the grid electricity used in the base case contains high fossil fuel shares.
  - The direct use of renewable electricity in plants for the liquefaction of SNG is more effective than operation with gas turbines in which the previously produced SNG is burned. This reduces impacts in SNG synthesis.
  - **The use of renewable electricity in all processes also leads to a reduction in environmental impacts in all other categories** except for the hemeroby-weighted land use, where slightly higher impacts occur.
- The use of carbon-based **PtGLS products as fuel** in shipping leads to savings in climate impact of 5–20%, depending on transport distance and energy source. At the same time, SO_2 emissions are eliminated by replacing heavy fuel oil, reducing the impact of transport in the categories of acidification, summer smog and particulate matter. The additional electricity required to produce PtGLS fuel reduces this effect, but does not reverse it. The additional electricity requirement has negative effects in the categories of cumulative energy consumption and land use, but these are small in percentage terms compared to the reductions in the other categories.
- In all processes that produce or use **ammonia**, effective exhaust gas treatment is important to eliminate emissions of nitrogen oxides and ammonia into the air.
  - The use of selective catalytic reduction (SCR) in exhaust gas treatment in processes for the production and cracking of ammonia can effectively reduce emissions of NO_X and NH_3. This leads to reductions in the environmental impact of these processes in the categories of acidification, eutrophication, summer smog and particulate matter of 70–90%.
- Based on current knowledge, the use of **ammonia as a fuel** should be viewed critically, as the following negative effects may occur:
  - According to current data, NH_3-powered marine engines produce climate-active N_2O emissions that offset the savings in fossil CO_2 emissions from the combustion of heavy fuel oil and can lead to higher climate impacts. There is uncertainty in the emission data because ammonia engines are not yet in use. In order to bring the environmental impact

to a level comparable to other modes of transport, avoiding ammonia slip and effective exhaust gas cleaning (SCR) are absolutely necessary.

- An alternative is to use carbon-based PtGLS products as fuel for the transport of ammonia.

- The use of **seawater desalination** to obtain process water for electrolysis leads to significant savings in fresh water in hydrogen production. The additional electricity requirement is around 0.1% of the electricity required for electrolysis. Accordingly, there are slightly higher environmental impacts in all categories. Seawater desalination generates process-related emissions of SO_2, which lead to a slight increase in environmental impacts in the categories of acidification, summer smog and particulate matter. This study did not quantify the environmental impacts that may arise from the discharge of brine, disruption of biodiversity in seawater or the use of antifouling and disinfectants.
- The use of **alternative membrane materials for electrolysis** that do not contain halogenated hydrocarbons, e.g. polysulphone membranes, significantly reduces the contribution to ozone depletion and has no identified negative effects in other impact categories.
- The use of **electric trucks** powered by renewable electricity to distribute PtGLS products in Germany reduces the climate impact of transport. However, the manufacture of the trucks, in particular the batteries, can lead to high additional burdens in the categories of resource and water demand, as well as a slight increase in the categories of eutrophication, ozone depletion and particulate matter.
- The production of **"blue" hydrogen** requires a number of measures that can significantly reduce its climate impact:
  - **Minimising methane losses** during the extraction, transport and storage of natural gas is crucial for the climate impact. This has already been demonstrated by the different climate impacts of natural gas from different producing countries. Production conditions can lead to a variation in the climate impact of "blue" hydrogen by a factor of more than two.
  - When selecting the reformer technology, **autothermal reforming (ATR)** is preferable to steam reforming (SMR) in terms of CO_2 capture options. Higher separation rates can be achieved through energy generation within the reactor, thereby reducing the climate impact.
  - The **highest** possible **separation efficiency for CO_2** from the product stream of the reformer is also important for a low climate impact. The target should be a separation efficiency of 98% (or higher).
  - The **permanent storage of the captured CO_2** without leaks or escapes due to accidents or other events is an essential prerequisite for "blue" hydrogen to achieve the low climate impact shown. Storage requires suitable storage sites, which are only available to a limited extent. These must be monitored for thousands of years and the storage space excludes alternative uses (raw material extraction, deep geothermal energy, wind turbines, etc.) for an indefinite period (several tens of thousands of years).

- Additional reductions in climate impact can be achieved by supplying all processes with renewable electricity, with the additional reduced environmental impacts in other categories as described above.
- Only by combining all these optimistic conditions "blue" hydrogen can achieve a similarly low climate impact as "green" hydrogen. In many cases, the production of "blue" hydrogen will have a higher environmental impact than the optimal results shown in this study.

The measures examined in this study aim at direct changes in the so-called foreground processes, i.e. measures that can be implemented directly by plant operators or demanded by distributors of PtGLS products, authorities or certification bodies along the process chain for PtGLS products. This achieves a lower limit for climate impacts in the range of 14–24 g CO_2-eq./MJ. Since the remaining environmental impacts originate from the so-called background system, they cannot be addressed by measures in the process chains for the production of PtGLS products themselves. To address these environmental impacts, processes in the background system must be defossilised and improved in other ways as well. The main driver for this is the expansion of renewable energies and the increase in the share of renewable energies in the electricity mix.

Zusammenfassung

Im Forschungsvorhaben *Kriterien für eine nachhaltige Bereitstellung und klimagerechte Integration von strombasierten erneuerbaren Energieträgern*, kurz NEET, wird untersucht, wie eine ökologisch und sozioökonomisch nachhaltige Erzeugung von PtGLS (Power to Gas, Liquids, Solids) Produkten erfolgen kann.

In diesem Kurzpapier erden die Umweltwirkungen von verschiedenen Prozessen und Prozesspfaden für die Herstellung von PtGLS-Produkten mittels Ökobilanzen (LCA) ermittelt und technische Maßnahmen zur Begrenzung der Umwelteffekte abgeleitet. Die folgenden Produkte stehen im Fokus dieser Studie:

- Wasserstoff (grün, blau, türkis)
- Ammoniak (grün, blau)
- Methan (grün)
- Methanol (grün)
- Dimethylether (grün)
- Benzin/Diesel/Kerosin/Naphtha (grün)

Abschnitt 2 listet die einzelnen Prozesse auf, aus denen sich die zu untersuchenden Pfade zur Herstellung dieser Produkte zusammensetzen. Sie werden als einzelne Datensätze mit den wichtigsten Parametern beschrieben. Eine ausführliche Darstellung der einzelnen Prozesse ist im separaten technischen Anhang als Excel-Tabelle gegeben. Dort sind alle Energie- und Materialflüsse jedes Prozesses aufgeführt.

Ausgehend von Erkenntnissen aus früheren Studien wird in Abschnitt 3 für jedes Produkt ein Basispfad definiert. Darüber hinaus werden Variationen der Basispfade durchgeführt, die die Einflüsse von z. B. Stromquelle, Transportmedium und Standort untersuchen.

In Abschnitt 4 werden die ermittelten Umweltwirkungen der untersuchten PtGLS-Bereitstellungspfade dargestellt. Dabei werden zunächst die methodischen Grundlagen der Berechnung beschrieben (Abschnitt 4.1), gefolgt von den Ergebnissen in den einzelnen Wirkungskategorien (Abschnitt 4.3).

In Abschnitt 5 werden technische Möglichkeiten aufgezeigt, die wichtigsten Umweltwirkungen zu verringern und es werden die Minderungseffekte quantifiziert.

Bereitstellungsprozesse

- Im allgemeinen Verständnis erfolgt die Erzeugung von PtGLS-Produkten unter Verwendung von erneuerbaren Energiequellen (EE). In dieser Studie werden Windkraftanlagen, Freiflächen-Photovoltaik und konzentrierende Solarkraftwerke betrachtet. Für die Modellierung werden länder- und regionenspezifische EE-Strommixe sowie Netzstrommixe herangezogen.
- „Grüner“ Wasserstoff wird mittels Elektrolyseanlagen hergestellt. Gegenstand der Modellierung sind sowohl die Alkalische Elektrolyse (AEL) als auch die Polymer-Elektrolyt-Membran-Elektrolyse (PEMEL). Im Detail betrachtet werden Energie- und Wasserbedarf sowie die Auswirkungen von polyfluorierten Membranen und deren Alternativen.

- Für „blauen“ Wasserstoff wird die Methanreformierung und anschließende Abscheidung von CO_2 (Carbon Capture and Storage, CCS) modelliert. Zur Herstellung von Wasserstoff aus Erdgas/Methan sind großtechnisch zwei Prozesse üblich: Dampfreformierung von Methan (SMR, Steam Methane Reforming), und Autotherme Reformierung von Methan (ATR, Autothermal Reforming).
- „Türkiser“ Wasserstoff wird durch Methanpyrolyse hergestellt. Die thermische Pyrolyse wandelt Methan in Wasserstoff und festen Kohlenstoff um.
- Für kohlenstoffbasierte PtGLS-Produkte wird CO_2 mittels Direct Air Capture (DAC) aus der Luft bereitgestellt und anschließend mit Wasserstoff zu den jeweiligen Produkten verarbeitet. Weitere betrachtete CO_2-Quellen sind Zementwerke, Müllverbrennungsanlagen und Biogasanlagen.
- Ammoniak ist eines der betrachteten Zielprodukte sowie Transportderivate für Wasserstoff. Zur Ammoniaksynthese wird das Haber-Bosch-Verfahren betrachtet; soll Wasserstoff zurückgewonnen werden, kommt eine Ammoniak-Spaltung zum Einsatz.
- Methan bzw. Synthetisches Erdgas (SNG) wird aus Wasserstoff und CO_2 hergestellt. Ebenso verläuft die Synthese von Methanol. Aus Methanol können im weiteren Prozessverlauf Dimethylether (DME) und Kraftstoffe mittels Methanol-to-Gasoline-Verfahren hergestellt werden. Des Weiteren wird die Herstellung von Kraftstoffen mittels Fischer-Tropsch-Verfahrens betrachtet.
- Der Bau sowie der Rückbau der Anlagen zur Produktion der PtGLS-Produkte werden in der Betrachtung der Umweltwirkungen berücksichtigt, inbegriffen der verwendeten Katalysatoren. Die Materialbedarfe werden verteilt auf die Gesamtmenge an Produkt, die über die Lebensdauer der Anlage hergestellt wird.
- Als Transportoptionen stehen verschiedene Möglichkeiten zur Verfügung. Diese sind z. B. der Transport von flüssigen Derivaten mittels herkömmlicher Tankschiffe und per Lkw, der Transport von Wasserstoff und SNG per Pipeline. Je nach Herkunftsland werden verschiedene Kurz- und Langstreckentransporte modelliert.

Prozessketten zur Herstellung von PtGLS-Produkten

Aus den verschiedenen Möglichkeiten die Prozesse miteinander zu kombinieren, wurden für insgesamt 56 Pfade zur Herstellung von PtGLS-Produkten Ökobilanzen berechnet. Die Prozessketten umfassen die Bereitstellung von Rohmaterialen und Energie in Form von Strom/Wärme, die Synthese von Wasserstoff, ggf. eine Umwandlung in Derivate, einen Transport nach Deutschland sowie ggf. eine Rückumwandlung zu Wasserstoff. Von den 56 Pfaden wurden 6 Pfade als Basisfälle festgelegt und 50 Pfade als Variationen mit Änderungen einzelner Prozessglieder ergänzt. Für die Umsetzung von Maßnahmen in (naher) Zukunft zur Minderung von Umwelteffekten wurden 12 weitere Zielszenarien abgebildet und berechnet.

Klima- und Umwelteffekte der PtGLS-Produkte

Die Analyse der Ökobilanzberechnungen zeigt, welche Faktoren maßgeblich die Umweltwirkungen bei der Bereitstellung synthetischer Energieträger auf Basis erneuerbarer Energien beeinflussen. Dabei werden auch mögliche Zielkonflikte zwischen unterschiedlichen Wirkungskategorien identifiziert – etwa dann, wenn niedrige Treibhausgasemissionen mit höheren Umweltbelastungen in anderen Bereichen einhergehen. Im Mittelpunkt steht die Bewertung der Klimawirkung synthetischer Energieträger und die Frage, inwieweit sie gegenüber fossilen Referenzprodukten ökologische Entlastungen bieten.

- Für die Produkte **Ammoniak, Methanol, DME und Fischer-Tropsch-Kraftstoffe** lässt sich in den betrachteten Basisfällen eine **Reduktion der Klimawirkung um rund 80 %** erreichen. Für **synthetisches Erdgas ist eine Reduktion um 60 %** möglich. Für **Wasserstoff**, der gebunden im Transportmedium Ammoniak verschifft wird, kann die Klimawirkung um rund **50 % sinken** – wenn erneuerbarer Strom auch zur Ammoniaksynthese eingesetzt wird.

- Die Nutzung von „**Graustrom", d. h. Netzstrom**, der in der Regel auch erhebliche Anteile aus nicht-erneuerbaren Quellen enthält, **verschlechtert die Klimabilanz** in allen Prozessschritten. Das gilt vor allem für die Nutzung in der Elektrolyse, aber auch in der Synthese, Verflüssigung oder Spaltung des Transportmediums und in der Stromversorgung von Pipelinekompressoren.

- Da die Lasten des erneuerbaren Stroms in den meisten Basisfällen zwischen 40–60 % der Klimawirkung ausmachen, hat die **Wahl der erneuerbaren Stromquelle** einen merklichen Einfluss auf das Gesamtergebnis. **Windkraft** ist die Quelle mit der **niedrigsten Klimawirkung** und weist zugleich nur kleine absolute Unterschiede pro kWh zwischen verschiedenen Standorten auf. Die Ergebnisse für Strom aus **Photovoltaik** zeigen **größere Unterschiede zwischen Standorten**, liegen aber auch im günstigsten Fall **zwei bis dreimal so hoch wie die für Windstrom.**

- Für die untersuchten **Transportoptionen für Wasserstoff** zeigt der Import per **Pipeline die geringste Klimawirkung**. Der Transport mit **LOHC und DME** als Transportmedium liegt **deutlich höher**. Wird das Transportmedium **Ammoniak** genutzt, kann dies mit den Ergebnissen des **Pipelinetransports** mithalten, jedoch nur wenn **erneuerbarer Strom für die NH_3-Synthese** eingesetzt wird. Andernfalls liegen die Klimalasten doppelt so hoch wie die des Pipeline-Transports.

- Der **Import von „blauem" und „türkisem" Wasserstoff** mit dem Transportmedium Ammoniak führt zu einer Klimawirkung, die **kaum besser oder sogar schlechter ist als die fossile Referenz.** Die Hauptgründe sind Treibhausgasemissionen in der Erdgasbereitstellung (insbesondere Methan) und CO_2-Emissionen in der Reformierung. Die Herstellung von „türkisem" Wasserstoff führt mit der hier untersuchten Technik zu schlechteren Ergebnissen als die von „blauem" Wasserstoff.

- Die **Herstellung von „blauem" Wasserstoff in Deutschland** könnte hingegen die Klimawirkung gegenüber der herkömmlichen Herstellung (Referenz) um **40–70 % senken.** Voraussetzung für eine möglichst starke Reduktion ist der **Import von Erdgas mit geringen Vorlasten** und der Einsatz des Verfahrens mit **möglichst hoher CO_2-Abscheidequote**. Nicht einbezogen ist der Volumenbedarf zur Speicherung (CCS) sowie mögliche Leckagen und Austritte von CO_2 aus den Speicherstätten.

- Die Wahl zwischen den untersuchten **Elektrolysetechniken** AEL und PEMEL macht **kaum einen Unterschied.**

- Zwischen der Produktion von erneuerbarem **Ammoniak** im untersuchten **Ausland** und der in **Deutschland** gibt es **keine großen Unterschiede**, da sich Vorteile der Stromerzeugung mit den Nachteilen des Transports fast ausgleichen.

- Für **synthetisches Methan** spielt der **Transport** eine erhebliche Rolle. Wie beim Wasserstoff ist auch hier der Transport per **Pipeline die Option mit den geringsten Lasten** für Entfernungen bis zu 3.000–4.000 km. Der verflüssigte **Transport per Schiff** ist

für **weitere Entfernungen vorteilhafter**, macht aber in der Regel die Vorteile höherer EE-Volllaststunden im fernen Ausland zunichte.

- Für die flüssigen Energieträger **Methanol, DME und Fischer-Tropsch-Kraftstoff** spielt die **Klimawirkung des genutzten EE-Stroms** eine größere Rolle, weil der Bedarf an Wasserstoff hoch ist. Der **Transport per Schiff** trägt im Vergleich zu den gasförmigen Energieträgern **weniger stark** bei.
- Die Klimalasten der Bereitstellung von Benzin über die **Methanol-to-Gasoline**-Route liegen rund **ein Viertel über denen der Fischer-Tropsch-Route**, aber dennoch **70 % unter der fossilen Referenz.**

Im Gegensatz zum Treibhauspotenzial zeigen die meisten Bereitstellungspfade in allen **anderen Wirkungskategorien eine deutliche höhere Umweltbelastung** im Vergleich zur jeweiligen fossilen Referenz:

- In der Kategorie „**Versauerung**“ schneiden insbesondere Pfade, in denen **Ammoniak** genutzt wird, **sehr schlecht** ab. Aber auch die Bereitstellung von **synthetischem Erdgas** und der flüssigen Energieträger **Methanol, DME und Fischer-Tropsch-Kraftstoffe** schneidet deutlich **schlechter als die fossile Referenz** ab. Grund sind vor allem Emissionen von Schwefeldioxid, Stickoxiden und Ammoniak in Hintergrundprozessen (Infrastruktur und Transporte).
- Die Bereitstellung der synthetischen Energieträger führt auch zu einer **vielfach erhöhten Eutrophierung (Überdüngung) gegenüber der fossilen Referenzen**. Auch die Eutrophierung wird zu großen Teilen durch Emissionen von Ammoniak und Stickoxiden verursacht, es kommen jedoch noch Phosphatemissionen ins Wasser hinzu – letzteres bei Nutzung von fossilem Netzstrom für Transportprozesse.
- In ihrem **Ozonabbaupotenzial** sind nur **Methanol und DME etwas besser** als die fossile Referenz. Die Basisfälle für Wasserstoff und Ammoniak liegen darüber. **Fischer-Tropsch-Kraftstoffe sind ein Vielfaches ozonschädlicher** als fossiler Diesel. Grund ist die Herstellung der Elektrolyseure, bei der Tetrafluorethylen in der Produktion der Membran eingesetzt wird.
- Das Potenzial für die Bildung von **Sommersmog** liegt für **Ammoniak, Methanol, DME und Fischer-Tropsch-Kraftstoffe** deutlich **unter der jeweiligen fossilen Referenz**. Die Bereitstellung von **synthetischem Erdgas und Wasserstoff** über das Transportmedium Ammoniak ist aber ein **Vielfaches schlechter**. Grund sind in allen Fällen Emissionen von Stickoxiden in Hintergrundprozessen (Transport, Infrastruktur).
- **Feinstaubemissionen** liegen potenziell **alle erheblich über denen der jeweiligen fossilen Referenz.** Für alle synthetischen Produkte tragen Emissionen von Stickoxiden aus Infrastruktur und Transportprozessen maßgeblich bei. Wird Netzstrom genutzt, kommen SO_2-Emissionen hinzu. Bereitstellungspfade mit Ammoniak führen über NH_3-Emissionen zu einem hohen Feinstaubpotenzial.
- Der **kumulierte Energieaufwand** liegt für fast alle synthetischen Produkte **gleichauf oder höher als für die jeweilige fossile Referenz.** Nur **Ammoniak und Methanol** benötigen in diesem Vergleich **etwas weniger Energieinput**. Maßgeblich ist in allen Fällen der Strominput in die Elektrolyse.

- Der **Flächenbedarf** der erneuerbaren Stromerzeugung ist der Grund dafür, dass die **hemerobiegewichtete Landnutzung** der synthetischen Produkte **rund 20–30-mal höher** liegt als die von fossilen Referenzprodukten.
- Der **Wasserbedarf** entsteht vor allem im Hintergrundsystem, insbesondere durch **fossile Stromerzeugungsanlagen und Infrastruktur**. Im Vordergrundsystem **dominiert der Kühlwasserbedarf für die Elektrolyse**, während der **Süßwasserbedarf für die Elektrolyse** im Vergleich dazu **gering** ist. Dennoch ist letzterer nicht zu vernachlässigen, da das Kühlwasser die Anlage wieder verlässt, während das Wasser für die Elektrolyse dauerhaft dem lokalen System entnommen wird.
- Auch für das **abiotische Ressourcenerschöpfungspotenzial für Mineralien und Metalle** zeigen alle Basisfälle in Bezug auf die jeweilige fossile Referenz einen **deutlichen Anstieg**. Grund ist der Bedarf für den Bau der Stromerzeugungs- und Syntheseanlagen.

Möglichkeiten zur Minderung von Umwelteffekten

Aus den identifizierten Umweltbelastungen wurden Maßnahmen abgeleitet, um die Umwelteffekte weiter zu mindern. Insgesamt führen sie in den meisten Fällen zu einer Verbesserung der Umweltbilanz; nur vereinzelt treten geringfügige Zielkonflikte auf. Die wichtigsten Maßnahmen und deren Auswirkungen sind:

- Die **regenerative Stromversorgung** aller Prozesse entlang der Wertschöpfungskette (ATR/SMR, NH_3-Synthese, NH_3- und LOHC-Spaltung, Gasleitungstransport, etc.), auch zur Wärmeversorgung ist wichtig für die Reduktion der Klimawirkung. Die Energiewende ist dabei eine Grundvoraussetzung, dass neben der Elektrolyse auch alle anderen Prozesse mit erneuerbarem Strom betrieben werden können.
  - Insbesondere die Versorgung der Derivatsynthese und ggf. deren Rückumwandlung mit erneuerbarem Strom anstelle von Graustrom und fossiler Wärme führt zu großen Verbesserungen in den Kategorien Klimawandel, Versauerung und Eutrophierung.
  - Auch der Betrieb von Gasfernleitungen und -distributionsnetzen mit EE-Strom führt zu Verbesserungen, insbesondere wenn der im Basisfall verwendete Netzstrom hohe fossile Anteile enthält.
  - Die direkte Nutzung von erneuerbarem Strom in Anlagen zur Verflüssigung von SNG ist effektiver als der Betrieb mit Gasturbinen, in denen das zuvor hergestellte SNG verbrannt wird. So werden Lasten in der SNG-Synthese reduziert.
  - **Die Nutzung von erneuerbarem Strom in allen Prozessen führt zusätzlich zu einer Verringerung der Umweltwirkungen in allen anderen Kategorien** außer in der hemerobiegewichteten Landnutzung, bei der geringfügig höhere Belastungen entstehen.
- Die Nutzung von kohlenstoffbasierten **PtGLS-Produkten als Treibstoff** beim Schiffstransport führt zu Einsparungen in der Klimawirkung von 5–20 %, abhängig von Transportdistanz und Energieträger. Gleichzeitig werden die Emissionen von SO_2 durch den Ersatz von Schweröl eliminiert, so dass sich die Belastung aus dem Transport auch in den Kategorien Versauerung, Sommersmog und Feinstaub verringert. Der zusätzliche Strombedarf für die Herstellung des PtGLS-Kraftstoffes verringert diesen Effekt, kehrt ihn aber nicht ins Negative um. Durch den zusätzlichen Strombedarf entstehen negative Effekte in den Kategorien Kumulierter Energieaufwand und Landnutzung, die jedoch prozentual klein sind im Vergleich zu den Entlastungen in den anderen Kategorien.

- In allen Prozessen, die **Ammoniak** herstellen oder nutzen, ist eine effektive Abgasnachbehandlung zur Eliminierung von Emissionen von Stickoxiden und Ammoniak in die Luft wichtig.
  - Durch Einsatz von selektiver katalytischer Reduktion (SCR) bei der Abgasnachbehandlung in den Prozessen zur Herstellung und Spaltung von Ammoniak können die Emissionen von NO_X und NH_3 effektiv reduziert werden. Das führt zu Reduktionen der Umweltwirkungen dieser Prozesse in den Kategorien Versauerung, Eutrophierung, Sommersmog und Feinstaub in Höhe von 70–90 %.
- Die Nutzung von **Ammoniak als Treibstoff** ist mit dem heutigen Wissensstand kritisch zu sehen, da folgende negative Effekte auftreten können:
  - Nach aktueller Datenlage entstehen in NH_3-betriebenen Schiffsmotoren klimaschädliche N_2O-Emissionen, die die Einsparung der fossilen CO_2-Emissionen bei Verbrennung von Schweröl überkompensieren und zu höheren Klimawirkungen führen können. Es besteht eine Unsicherheit in den verwendeten Emissionsdaten, weil Ammoniakmotoren bislang noch nicht im Einsatz sind. Um die Umweltwirkung auf ein Maß zu bringen, das vergleichbar ist mit den anderen Transportwegen, sind die Vermeidung von Ammoniak-Schlupf sowie eine effektive Abgasreinigung (SCR) unbedingt notwendig.
  - Als Alternative bietet sich an, beim Transport von Ammoniak kohlenstoffbasierte PtGLS-Produkte als Treibstoff zu verwenden.
- Der Einsatz von **Meerwasserentsalzung** zur Gewinnung von Prozesswasser für die Elektrolyse führt zu einer deutlichen Einsparung von Süßwasser in der Wasserstoff-Erzeugung. Der zusätzliche Strombedarf liegt bei etwa 0,1 % bezogen auf den Strombedarf der Elektrolyse. Entsprechend gibt es geringfügig höhere Umweltwirkungen in allen Kategorien. Bei der Meerwasserentsalzung entstehen prozessbedingt Emissionen von SO_2, die zu einer leichten Erhöhung der Umweltlasten in den Kategorien Versauerung, Sommersmog und Feinstaub führen. Eine Quantifizierung von Umweltlasten, die durch Einleitung der Sole, der Störung der Biodiversität im Meerwasser oder durch Antifouling- und Desinfektionsmittel entstehen können, wurde in dieser Studie nicht durchgeführt.
- Die Verwendung von **alternativen Membranmaterialien**, für die keine halogenierten Kohlenwasserstoffe eingesetzt werden, z. B. Polysulfon-Membranen, reduziert den Beitrag zum Ozonabbau deutlich und hat keine festgestellten negativen Effekte in anderen Wirkungskategorien.
- Die Nutzung von **elektrisch betriebenen Lkw**, die mit regenerativem Strom zur Distribution der PtGLS-Produkte in Deutschland versorgt werden, führt zu einer Reduktion der Klimawirkung im Transport. Die Herstellung des Lkw, insbesondere der Batterie können jedoch zu hohen zusätzlichen Lasten in den Kategorien Ressourcenbedarf und Wasserbedarf sowie zu geringer Erhöhung der Belastungen in den Kategorien Eutrophierung, Ozonabbau und Feinstaub führen.
- Bei der Herstellung von **„blauem“ Wasserstoff** sind einige Maßnahmen notwendig, die insbesondere die Klimawirkung stark reduzieren können:
  - Die **Minimierung von Methanverlusten** bei Förderung, Transport und Speicherung von Erdgas ist von entscheidender Bedeutung für die Klimawirkung. Dies wurde bereits anhand der unterschiedlichen Klimalasten von Erdgas aus verschiedenen

Produktionsländern gezeigt. Die Produktionsbedingungen können zu einer Variation der Klimawirkung von „blauem“ Wasserstoff um einen Faktor von mehr als zwei führen.

- Bei der Auswahl der Reformertechnik ist das Verfahren der **autothermen Reformierung (ATR)** in Bezug auf die Möglichkeiten zur CO_2-Abscheidung der Dampfreformierung (SMR) vorzuziehen. Durch die Energieerzeugung innerhalb des Reaktors können höhere Abscheideraten erreicht werden, wodurch die Klimawirkung reduziert wird.
- Ein möglichst **hoher Abscheidegrad für CO_2** aus dem Produktstrom des Reformers ist zusätzlich wichtig für eine niedrige Klimawirkung. Ziel sollte ein Abscheidegrad von 98 % (oder höher) sein.
- Die **dauerhafte Speicherung des abgeschiedenen CO_2** ohne Leckagen oder Austritte durch Unfälle oder andere Ereignisse ist wesentliche Grundvoraussetzung dafür, dass „blauer“ Wasserstoff die gezeigten niedrigen Klimawirkungen erreicht. Die Einspeicherung benötigt geeignete Lagerstätten, die nur in begrenztem Umfang verfügbar sind. Diese sind über Jahrtausende nachzubetreuen und der Speicherraum schließt alternative Nutzungen (Rohstoffgewinnung, tiefe Geothermie, Windenergieanlagen, etc.) auf unbestimmte Zeit (mehrere zehntausend Jahre) aus.
- Zusätzliche Reduktionen in der Klimawirkung sind durch die Versorgung aller Prozesse mit regenerativem Strom erreichbar mit den zusätzlichen reduzierten Umweltwirkungen in anderen Kategorien wie oben beschrieben.
- Nur durch die **Kombination aller dieser optimistischen Rahmenbedingungen** kann erreicht werden, dass „blauer“ Wasserstoff ähnlich niedrige Klimawirkungen erzielt wie „grüner“ Wasserstoff. In vielen Fällen wird die Herstellung von „blauem“ Wasserstoff höhere Umweltwirkungen haben, als die in dieser Studie gezeigten optimalen Ergebnisse.

Die in dieser Studie untersuchten Maßnahmen zielen auf direkte Änderungen in den sogenannten Vordergrundprozessen ab, sind also Maßnahmen, die Betreiber von Anlagen direkt umsetzen können, bzw. Händler von PtGLS-Produkten, Behörden oder Zertifizierungsstellen entlang der Prozesskette für PtGLS-Produkte einfordern können. Dabei wird eine Untergrenze bei den Klimawirkungen im Bereich von 14–24 g CO_2-Äq / MJ erreicht. Da die verbleibenden Umwelteffekte aus dem sogenannten Hintergrundsystem stammen, sind sie durch Maßnahmen an den Prozessketten zur Herstellung von PtGLS-Produkten selbst nicht adressierbar. Um diese Umwelteffekte anzugehen, müssen Prozesse im Hintergrundsystem defossilisiert und auch in anderen Aspekten verbessert werden. Maßgeblicher Treiber hierfür ist der Ausbau von erneuerbaren Energien, bzw. die Steigerung des EE-Anteils im Strommix.

1 Introduction and background

The research project *"Criteria for the sustainable provision and climate-friendly integration of electricity-based renewable energy sources*" ("NEET" for short) is investigating how PtGLS (Power to Gas, Liquids, Solids) products can be produced in an ecologically and socio-economically sustainable manner. To this end, the environmental impacts of the manufacture and transport of PtGLS products up to their provision in Germany are being investigated, and socio-economic criteria are being developed with which potential sites that have a high technical potential for the manufacture of PtGLS products can be evaluated.

This brief paper contains the results of work package 3, which aims to determine the environmental impacts of various processes and process paths for the production of PtGLS products and to derive technical measures to limit these environmental impacts. The following products are the focus of this study:

- Hydrogen (green, blue, turquoise) (see text box "Hydrogen colours")
- Ammonia (green, blue)
- Methane (green)
- Methanol (green)
- Dimethyl ether (green)
- Petrol/diesel/kerosene/naphtha (green)

Section 2 lists the individual processes that make up the pathways for manufacturing these products. They are described as individual data sets with the most important parameters. A detailed description of the individual processes is provided in a separate technical appendix in the form of an Excel table. This table describes all energy and material flows for each process.

Based on findings from previous studies, Section 3 defines a baseline path for each product that appears to be particularly realistic for the near future. In addition, variations of the baseline paths are specified, such as power source, transport medium and location, which promise to yield valuable insights into the key factors influencing the environmental impact of manufacturing.

Section 4 presents the environmental impacts of the PtGLS supply paths examined. First, the methodological basis for the calculation is described (section 4.1), followed by the results in the individual impact categories (section 4.3).

Section 5 outlines ways to reduce the most significant environmental impacts and quantifies the mitigation effects.

Hydrogen colours

Hydrogen gas is produced by using various processes to remove hydrogen atoms from more complex molecules (e.g. H_2O, CH_4) and synthesise H_2 from them. These processes are energy-intensive and sometimes generate emissions such as CO_2. Depending on the source molecule, energy source and production process, different colours are attributed to the hydrogen product. These "colours" merely correspond to a description of the production history of the hydrogen. The downstream products synthesised from hydrogen (PtGLS) inherit the corresponding colour designations from hydrogen production.

- **Green hydrogen** is produced by electrolysis of water using electricity exclusively from renewable energies. More about green hydrogen in section 2.2.
- **Blue hydrogen** is produced via steam reforming of methane. Production is based on fossil fuels, and CO_2 emissions are unavoidable. If these emissions from steam reforming are removed using carbon capture and storage (CCS) and the carbon is stored, the hydrogen produced is labelled "blue". More on blue hydrogen in section 2.3.
- **Turquoise hydrogen** is produced during methane pyrolysis. Unlike steam reforming, the carbon from fossil methane is not converted into CO_2 but into solid carbon that can be stored. The hydrogen produced in this process is "turquoise". More on turquoise hydrogen in section 2.4.

In the case of green, blue and turquoise hydrogen, CO_2 emissions are either excluded from the process (renewable electricity, solid C from pyrolysis) or subsequently captured and stored in reservoirs (CCS).

- Other hydrogen colours are distinguished, but are not relevant in the context of this report: "grey" hydrogen is produced by steam reforming methane without CCS or by electrolysis of water using electricity sources that are not entirely renewable. When biomass is used as an energy source, the hydrogen is referred to as "orange". When lignite or hard coal is gasified, "brown" or "black" hydrogen is produced. Hydrogen obtained from natural (geological) sources is referred to as "white". If electricity from nuclear power plants is used for electrolysis, the hydrogen is referred to as "red" (in some sources also "pink" or "yellow").

2 Supply processes for PtGLS products

2.1 Power sources

It is generally understood that PtGLS products are produced using renewable energy sources. This study considers the following renewable electricity sources:

- Wind power at inland/coastal locations (wind turbines)
- Ground-mounted photovoltaics (PV)
- Concentrating solar power plants (CSP)

The renewable energy sources mentioned were selected because they can be established as additional sources of electricity in many regions with comparatively little effort. In particular, the expansion of renewable energies is assumed here, i.e. plants built in addition to existing power generation facilities. This additionality is crucial for the production of PtGLS products, as otherwise the additional demand for renewable electricity would reduce the availability of renewable energies for other sectors and thus delay the overall decarbonisation of the energy sector (see also Fehrenbach and Fröhlich, 2026). Other renewable electricity sources, such as geothermal energy, bioenergy and hydropower, are not considered in the modelling because they are only suitable for specific locations and can, in some cases, have a significant environmental impact. The TextBox on page 38 explains the environmental impacts of hydropower, which mean that this technology is not considered a sustainable energy source for increasing energy demand in this study.

In addition to the direct use of the aforementioned electricity sources wind energy, PV and CSP, it is assumed that electricity from these sources can be stored (e.g. via VRF = vanadium redox flow electricity storage) and used at a later point in time to operate electrolysis with an increased number of full-load hours; The use of stored electricity is referred to below as an "electricity source" in the sense of an additional life cycle stage of provision. The use of temporarily stored electricity accordingly includes the environmental impacts associated with the provision of storage infrastructure and losses.

For the selected locations, country-specific renewable electricity mixes are used in the base case, which are composed of the corresponding renewable electricity sources listed above. The renewable electricity mixes were selected to correspond to the current shares of PV, wind turbines and CSP in the countries studied. This is based on the assumption that the expansion will be uniform for all renewable electricity sources and that there will be no significant expansion of hydropower, biogas/biomass, geothermal energy and waste incineration. This assumption is highly simplistic, but it significantly reduces the effort that would be required to consider individual expansion paths.

Selected parameters are presented below for comparison of the locations examined: Table 1 shows the assumed full-load hours of the power generation plants. Table 2 contains the greenhouse gas potentials for the generation of 1 kWh of electricity from these power generation plants per location. The composition of the renewable energy mix per country is shown in Table 3, together with the resulting carbon footprint per kWh of electricity in Table 4.

Table 1: Full-load hours of various power generation plants in the considered generation regions in hours (h). Reference year: 2022

Location	Wind inland location	Wind coastal location	Photovoltaic open ground	Concentrating solar power plants
Germany (DE)	2,400	4,000	950	N/A
North Africa and Middle East (MENA)*	3,200	4,000	1,600	6,890
Australia (AU)	4,000	4,000	1,481	N/A
Chile (CL)	6,000	6,000	1,848	N/A
United States (US)	3,700	4,000	1,490	N/A
South Africa (ZA)	2,875	3,110	1,660	N/A
Canada (CA)	4,520	4,550	650	N/A
Spain (ES)	2,300	5,400	1,450	N/A
Denmark (DK)	4,200	5,200	950	N/A

* Here: average value from the United Arab Emirates (AE) and Morocco (MA)

n/a: no data available

Source: PtX Atlas (Pfennig et al. 2021, 2023), ES, DK: https://globalwindatlas.info and https://globalsolaratlas.info/

In all cases considered, renewable electricity has greenhouse gas (GHG) and other environmental impacts that are greater than zero. No direct GHG emissions are generated during the operation of renewable energy plants, apart from minor losses of the greenhouse gas SF_6, which is used in existing switchgear and will no longer be permitted for use in the future. The main environmental impact arises during the production and construction as well as the disposal and dismantling of renewable energy plants. These environmental impacts are divided by the total amount of energy produced by the renewable energy plant during its lifetime, resulting in the environmental impact per kWh.

In some variations of the base cases and for the power supply of plants for the production of blue and turquoise hydrogen, as well as blue ammonia, the country-specific grid electricity, which also contains fossil fuels, is used. The associated greenhouse gas emissions are shown in Table 2.

If required in the process chain, the same electricity source is used for the production of electrolytic hydrogen, CO_2 capture and auxiliary power in the synthesis plants.

Table 2: Carbon footprint of various power generation plants at different locations in g CO_2 eq./kWh. Reference year: 2022

	Unit	Wind inland location	Wind coastal location	Photovoltaic open ground	Concentrating solar power plants	Electricity storage VRF battery**
Service life	Years	20	20	25	25	20
Power per system	MW	6	15	-	50	-
Germany (DE)	g CO_2 eq./kWh	12	10	52	-	36

	Unit	Wind inland location	Wind coastal location	Photovoltaic open ground	Concentrating solar power plants	Electricity storage VRF battery**
North Africa and Middle East (MENA)*	g CO_2 eq./kWh	9	10	32	40	36
Australia (AU)	g CO_2 eq./kWh	7	10	34	-	36
Chile (CL)	g CO_2 eq./kWh	7	7	27	-	36
USA (US)	g CO_2 eq./kWh	-	10	33	-	36
South Africa (ZA)	g CO_2 eq./kWh	-	13	30	-	36
Canada (CA)	g CO_2 eq./kWh	-	9	-	-	36
Spain (ES)	g CO_2 eq./kWh	-	7	34	-	36
Denmark (DK)	g CO_2 eq./kWh	-	8	52	-	36

* here: average value from the United Arab Emirates (AE) and Morocco (MA)

** excluding electricity supply

- : no information available

Source: Own calculations based on SYSEET (Liebich et al. 2021), REFINE (Dittrich et al. 2025) and PtX-Atlas (Pfennig et al. 2021, 2023).

Table 3: Composition of the RE electricity mix (wind, PV, CSP) at different locations and resulting carbon footprint per kWh*. Reference year: 2022

Electricity source	Wind inland location	Wind coastal location	Photovoltaics Open ground	Concentrating solar power plants	Resulting carbon footprint
Germany (DE)	53%	14%	33%	0%	25 g CO_2 eq./kWh
North Africa and Middle East (MENA)**	39%	0%	53%	8%	23 g CO_2 eq./kWh
Australia (AU)	46%	0%	54%	0%	21 g CO_2 eq./kWh

*excluding biogas/biomass, geothermal energy, hydropower and waste incineration

**here: average value from the United Arab Emirates (AE) and Morocco (MA)

Source: Eurostat (https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ured/default/table), IEA (https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser), own calculations based on (Fröhlich et al. 2024)

Table 4: Carbon footprint of grid electricity in selected countries in g CO_2 eq./kWh. Reference year: 2022 for Germany, otherwise 2021

Country	g CO_2 eq./kWh
Germany (DE)	481
Middle East / North Africa (MENA*)	822

Country	g CO_2 eq./kWh
United Arab Emirates (AE)	586
Morocco (MA)	1057
Australia (AU)	80
Chile (CL)	526
United States (US)	487
South Africa (ZA)	1242
Canada (CA)	190
Spain (ES)	204
Denmark (DK)	185

*here: average value from United Arab Emirates (AE) and Morocco (MA)

Source: own calculation ifeu electricity model ELMO (Fröhlich et al. 2024)

TextBox: Environmental impacts of hydropower

Hydropower is one of the oldest sources of energy used by humankind and is also considered an important renewable energy source. However, both the use of flowing waters and reservoirs have a wide range of ecological and socio-economic impacts.

Hydropower generation is potentially possible all year round and regardless of weather conditions. It can be operated flexibly and can both fill gaps in renewable electricity generation from other sources and ensure a basic supply. However, the technical expansion potential for hydropower plants in Germany is very low. Depending on the circumstances, the share of electricity generation is significantly higher in the Alpine countries and Scandinavia, for example, but further expansion is only possible to a limited extent there as well (IHA 2024). Worldwide, there is great potential for hydroelectric power generation, especially outside Europe, but this is mainly based on the construction of large dams (IHA 2024).

In 2001, the World Commission on Dams published a report (Commission On Dams 2001), which critically examines the ecological and social impacts of dam projects. The key findings with regard to environmental impacts are as follows:

Large dams have profound and irreversible environmental impacts, including the loss of forests, wetlands and farmland and, as a result, the extinction of species.

Twenty per cent of the land irrigated by large dams is lost to salinisation and waterlogging, and five per cent of the world's fresh water evaporates from reservoirs.

Reservoirs emit greenhouse gases through the decomposition of flooded vegetation and soils, as well as organic material that flows into the reservoir from the catchment area.

2.2 Hydrogen from water electrolysis ("green hydrogen")

Hydrogen from electrolysis is considered "green" if the electrolyser is powered by renewable electricity, regardless of the electrolysis technology used. Specifically, the Renewable Energy Directive (Directive EU 2023/2413; "Renewable Energy Directive III", hereinafter "RED III" (European Parliament and Council of the European Union 2023) and associated delegated

regulations (2023/1184 and 2023/1185 (European Commission 2023a; b)) defines that "green" hydrogen must meet the following conditions to be considered an RFNBO (Renewable fuel of non-biological origin):

- Production entirely from renewable electricity sources, without electricity from biomass
- Direct connection of the electrolysis to the renewable electricity source and exclusive supply via this source. Alternatively, electricity is supplied from an electricity grid with either
  - a high renewable share (> 90%)
  - or low GHG intensity (< 18 g CO_2 eq./MJ)

In the latter case, a purchase agreement for renewable electricity and proof of the temporal and geographical proximity of electricity production to electricity consumption are also required.

- Furthermore, it must be demonstrated that the electricity generation takes place in addition to the existing electricity generation facilities and does not result in other consumers being able to purchase less renewable electricity. This means that the electricity generation facility has not received any subsidies in the form of operating or investment aid.

A more detailed examination of the criteria for RFNBO was carried out in a separate short paper (Fehrenbach and Fröhlich 2026).

This study considers two electrolysis techniques:

- alkaline electrolysis (AEL) using aqueous potash or caustic soda as the electrolyte, and
- polymer electrolyte membrane electrolysis (PEMEL) with a proton-conducting membrane as the electrolyte.

AEL is an established process that is used on an industrial scale worldwide. The advantages of AEL over PEMEL are lower investment costs, stable operation and a lower demand for critical raw materials (e.g. iridium). PEMEL offers potential advantages over AEL, which is why it is the subject of numerous research projects and is also already being used on an industrial scale. The advantages of PEMEL over AEL are: The current density is higher, so that it can be dimensioned smaller for the same power output. In addition, PEMEL can withstand higher and faster load fluctuations or load stage changes than AEL and requires shorter start-up times from cold standby. This flexibility makes PEMEL interesting for use with renewable energies that are subject to fluctuations, such as wind energy, and for grid-supporting operation.

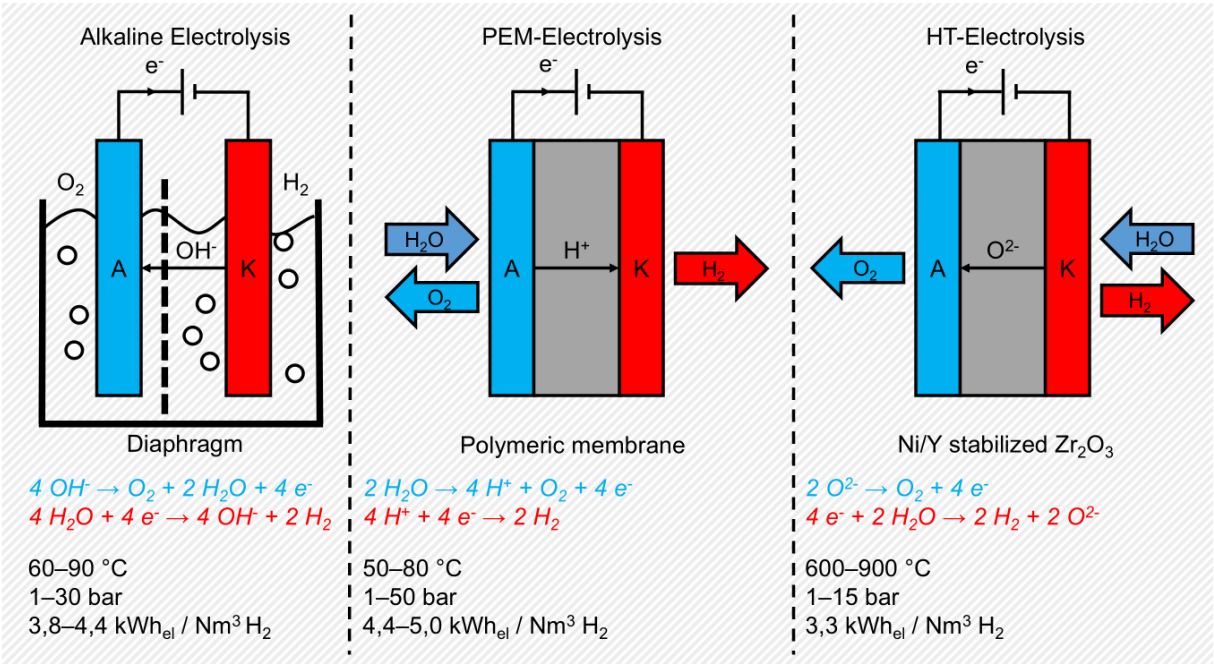
Although the total power requirement for high-temperature electrolysis (HTE or solid oxide electrolysis cell SOEC) to produce hydrogen is significantly lower than for AEL and PEMEL, HTE is not considered further in this study. Overall, the high temperatures required for HTE lead to greater challenges in terms of plant design, a shorter plant service life and higher overall costs for hydrogen production compared to AEL or PEMEL. In addition, the high temperatures required for HTE make flexible operation difficult when electricity availability fluctuates, so that HTE is preferably used in continuous operation due to its long start-up times. AEL and PEMEL are not affected by these limitations due to their significantly lower temperature levels. Furthermore, AEL and PEMEL are more advanced in terms of their development status[1].

AEL and PEMEL differ in their design and operating parameters. The basic principle of electrolysis is based on the splitting of water into hydrogen and oxygen by applying a direct

[1] The Technology Readiness Level (TRL) of HTE is 5-7, compared to PEMEL 7-9 and AEL 9 (Rosental et al. 2024).

electrical voltage. Hydrogen is deposited at the cathode of the setup, while oxygen forms at the anode. The operating modes of AEL, PEMEL and HTE are shown schematically in Figure 1.

Figure 1: Schematic overview of the three water electrolysis processes: alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEMEL) and high-temperature electrolysis (HTE).



AEL, PEMEL and HTE with electrode equations; technical parameters operating temperature, cell voltage and energy consumption at the stack. A = anode (blue), K = cathode (red).
Source: (Rosental et al. 2024)

Based on the stoichiometry of the reaction, the consumption of treated, deionised water for electrolysis is 9 kg per kilogram of hydrogen produced; according to (Saravia et al. 2024), a total of 10 kg of ultrapure water is required per kilogram of hydrogen. The amount of raw water required to produce the ultrapure water and the corresponding losses are influenced by the original water quality and the purification processes used: between 12 and 13 kg (surface water) and 20-30 kg (seawater) of raw water are required per kg of hydrogen.

In addition to water for electrolysis, water is also required for process cooling. Water demand refers to the total amount of water supplied. The water is either returned to the original water body after being heated or permanently removed from it and thus consumed. Water consumption occurs during the electrolysis of water, firstly through evaporative cooling and secondly through the discharge of fresh water (cooling water) into salt water bodies near the coast. The choice of cooling system for electrolysis influences the water demand and consumption (Saravia et al. 2024):

- continuous cooling, for example with river water, has a high water requirement in the range of 920-2,450 kg/kg H_2, but only very low water consumption of less than 1 kg/kg H_2.
- In contrast, a cooling water recirculation system with evaporative cooling has a water requirement of 17-40 kg/kg H_2; since a large part of the water evaporates during cooling, the water consumption of 10-25 kg/kg H_2 is significantly higher than that of continuous cooling.

- In air cooling or dry cooling systems as an alternative to water cooling, an evaporative cooling tower is replaced by a dry cooling tower, which reduces water consumption by approx. 95% compared to evaporative cooling. At the same time, however, the energy requirement for dry cooling systems increases by a factor of 1.6–4 due to the higher temperature of the air compared to water (European Commission 2001).

In addition to the actual demand for water, cooling has other potential environmental impacts, for example, continuous flow cooling discharges the absorbed heat into surface waters with the cooling water used, while evaporative cooling is responsible for the release of water vapour and latent heat into the atmosphere. At the same time, substances used for cooling water treatment or resulting from cooling water use, such as increased salt concentrations, can be released into the environment.

The choice of cooling system may be influenced by location factors; examples include the availability of water at the site or existing infrastructure in industrial parks. This study assumes a recirculation system with evaporative cooling and a cooling water requirement of 40 litres per kilogram of hydrogen. The water consumption of the electrolysis itself in this study is 12.6 litres of raw water (surface water) per kilogram of hydrogen (Saravia et al. 2024).

The environmental impacts of hydrogen production include both the burdens of providing water, energy and operating resources and – deviating from the definition in EU regulations – the production of the infrastructure and the electrolyser itself. The parameters of service life and production volume, determined by the utilisation and operating hours of the electrolyser, influence the extent to which the environmental impacts from these areas of production are attributed to one kilogram of hydrogen. In particular, the environmental impact associated with the manufacture of the electrolyser is distributed as an annual impact over its service life; regular replacement of the stacks is taken into account in the environmental assessment, but not their disposal. The occupancy of industrial area is assumed to be 90 m^2 per MW_{el} power consumption.

There are various sources of literature on system efficiency in particular, with this study based on (Smolinka et al. 2018), as shown in Table 5. The system efficiency of hydrogen production describes the system consisting of the efficiency of the stacks and other processes of the electrolysis system. Over the years, an increase in efficiency for AEL and PEMEL is assumed in the future. The efficiencies of PEMEL are below those of AEL for all years, as AEL technology is more mature and established than PEMEL.

Table 5: System efficiencies of the modelled electrolysis technologies AEL and PEMEL.

Electrolysis technology		System efficiency* [%]		
	Year	2017	2025	2030
Alkaline electrolysis		64.6	66.5	67.8
Polymer electrolyte membrane electrolysis		61.7	61.9	62.1

* System efficiency = LHV hydrogen produced relative to the amount of electricity required for the entire system consisting of the electrolysis stack and other components of the electrolysis plant (pumps, compressors, system electronics)
Source: derived from (Smolinka et al. 2018)

The material requirements for the electrolysers for the production of 1 MJ of hydrogen (equivalent to 8 g) are listed in Table 6. The iridium required in PEMEL stacks is an extremely rare element (current production approx. 8-9 t/year (National Hydrogen Council 2023)), which is used for PEMEL as a catalyst coating on the anode. Current research projects are looking into

ways of reducing the amount of iridium required. Other materials such as titanium and platinum are far less critical than iridium. PTFE (polytetrafluoroethylene) is used for the membrane in AEL and PEMEL, with the demand for AEL being about three times higher than for PEMEL. It is not yet clear whether the gradual ban on perfluorinated compounds (PFAS) announced on 20 September 2024 as part of an EU regulation (2024/2462)[2] will affect electrolysis technology in the coming years.

The electricity requirements listed in Table 6 refer to the manufacture of the electrolysers and are sourced from the electricity grid.

Table 6: Material and energy requirements for the manufacture of electrolysers, based on the production of 1 MJ of hydrogen

Material	Unit	AEL	PEMEL	AEL for 1 kg H_2	PEMEL for 1 kg H_2
Steel	kg	1.2E-04	5.8E-05	1.44E-02	6.96E-03
Cast iron	kg	2.1E-06	3.2E-06	2.52E-04	3.84E-04
Copper	kg	1.8E-06	1.9E-06	2.16E-04	2.28E-04
Aluminium	kg	4.6E-07	1.6E-06	5.52E-05	1.92E-04
Nickel	kg	9.3E-06	-	1.12E-03	-
Titanium	kg	-	4.5E-06	-	5.40E-04
Platinum	kg	-	6.3E-10	-	7.56E-08
Iridium*	kg	-	6.8E-09	-	8.16E-07
Plastic	kg	2.0E-06	4.7E-06	2.40E-04	5.64E-04
Zirconium	kg	2.4E-07	-	2.88E-05	-
PTFE	kg	4.7E-07	1.4E-07	5.64E-05	1.68E-05
Polysulphone	kg	1.6E-07	-	1.92E-05	-
Fibreglass	kg	1.3E-06	-	1.56E-04	-
Concrete	kg	2.2E-08	1.2E-08	2.64E-06	1.44E-06
Electricity	kWh	4.2E-04	1.1E-03	5.04E-02	1.32E-01

Service life and operating hours according to Table 18.

*Modelling of rhodium as a proxy for iridium according to (Krishnan et al. 2024).

Source: (Bareiß et al. 2019; Gerloff 2021; Koj et al. 2017)

2.3 Hydrogen from steam reforming of methane ("blue hydrogen ")

"Blue hydrogen" here refers to the production of hydrogen via steam reforming from fossil methane with subsequent carbon dioxide capture and storage (CCS). The electricity sources used refer to the respective grid electricity and are not necessarily renewable.

Two processes are commonly used on an industrial scale to produce hydrogen from natural gas/methane:

[2] https://eur-lex.europa.eu/eli/reg/2024/2462/oj/eng

- Steam methane reforming (SMR) and
- autothermal reforming of methane (ATR).

In addition to the process parameters of reforming and CO_2 capture (including CO_2 transport and storage), the environmental impacts of the extraction, processing and transport of the raw material natural gas, from which the methane for reforming is obtained, must also be taken into account. This includes methane emissions from extraction and processing according to the IEA Methane Tracker (IEA 2022).

During reforming, methane (CH_4) reacts with water vapour (H_2O) in the reformer to form hydrogen (H_2) and carbon monoxide (CO):

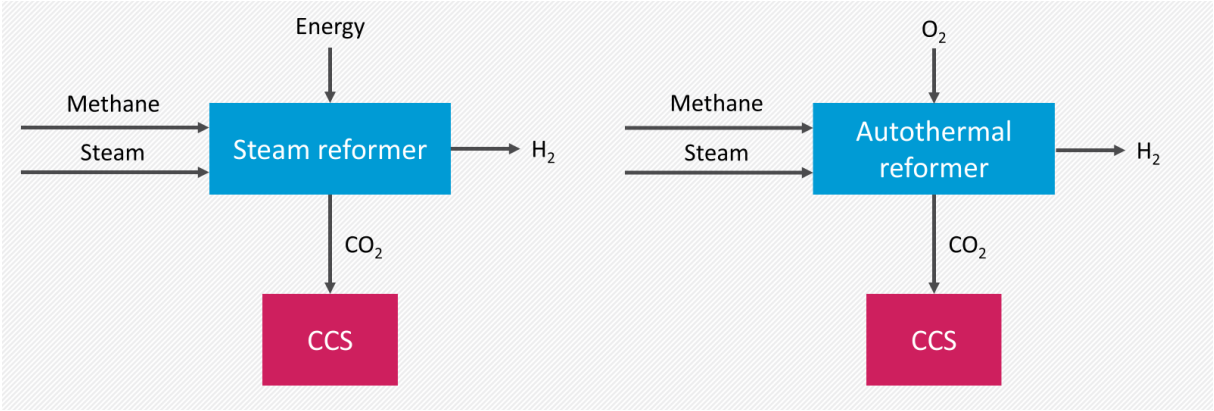
$$CH_4 + H_2O \rightarrow 3\ H_2 + CO$$

This process is endothermic and, in the case of SMR, requires an energy input in the form of heat. The water gas shift reaction of CO with water vapour further increases the hydrogen yield:

$$CO + H_2O \rightarrow CO_2 + H_2$$

This reaction is also endothermic and requires a heat supply. Unlike SMR, ATR does not require an external heat supply (from the combustion of natural gas). In ATR, the heat required is generated in the reactor by the supply of (pure) oxygen, which oxidises part of the methane with the formation of heat. The hydrogen is purified and the resulting residual gases are burned to generate steam. Excess steam is used in a steam turbine to generate electricity. In steam reforming, this can cover the plant's electricity requirements and part of the subsequent compression energy for transporting the hydrogen. Autothermal reforming, on the other hand, requires additional electricity from the grid.

Figure 2: Process diagram of SMR and ATR with CCS.



Source: Own representation, ifeu.

The CO_2 to be separated is produced in the SMR process, firstly during reforming through the oxidation of carbon from the raw material natural gas, and secondly during the necessary heat generation through the combustion of natural gas and residual gases from hydrogen purification. It only makes economic sense to capture the CO_2 from the synthesis gas after reforming. To avoid a higher proportion of emissions, capture after combustion for heat generation would be necessary (not assumed here).

In ATR, the combustion of residual gases from hydrogen production is the only source of direct CO_2 emissions, as no additional heat supply is required. In ATR, post-reforming capture already accounts for the majority of process-related CO_2 emissions. The CO_2 capture rates (after

reforming) differ significantly between SMR and ATR (see CO_2 storage, residual emissions and capture rates in Table 7). The captured CO_2 is dried and liquefied for transport and storage (Antonini et al. 2020).

Operating parameters were taken from the study by Antonini et al. (2020). Table 7 shows a selection of the most important energy requirements and CO_2 emissions. The generic data set "chemical factory construction, organics" from the ecoinvent LCA database (ecoinvent 2024; Wernet et al. 2016) was used for the construction and dismantling of the plants (see also section 2.13), supplemented by catalysts based on Al_2O_3/Cr/Cu/Mg/Mb/Ni. Details can be found in the Excel table in the separate technical appendix.

Table 7: Selected operating parameters for the production of 1 MJ LHV "blue" hydrogen via steam reforming (SMR) and autothermal reforming (ATR).

	Unit	SMR with CCS	ATR with CCS
Natural gas requirement	Nm^3	0.038	0.038
Electricity demand (from external sources)	kWh	-0.002 (surplus)	0.005
Process water requirement	kg	0.037	0.037
Cooling water requirement	kg	0.003	0.003
CO_2 storage	kg	0.047	0.064
CO_2 emissions into the air	kg	0.026	0.011
CO_2 capture rate (reformer)		90	90
CO_2 separation rate (system)		64	86

Source: (Antonini et al. 2020); LHV of hydrogen = 120 MJ/kg

Information on the transport and storage of CO_2 can be found in section 2.16.

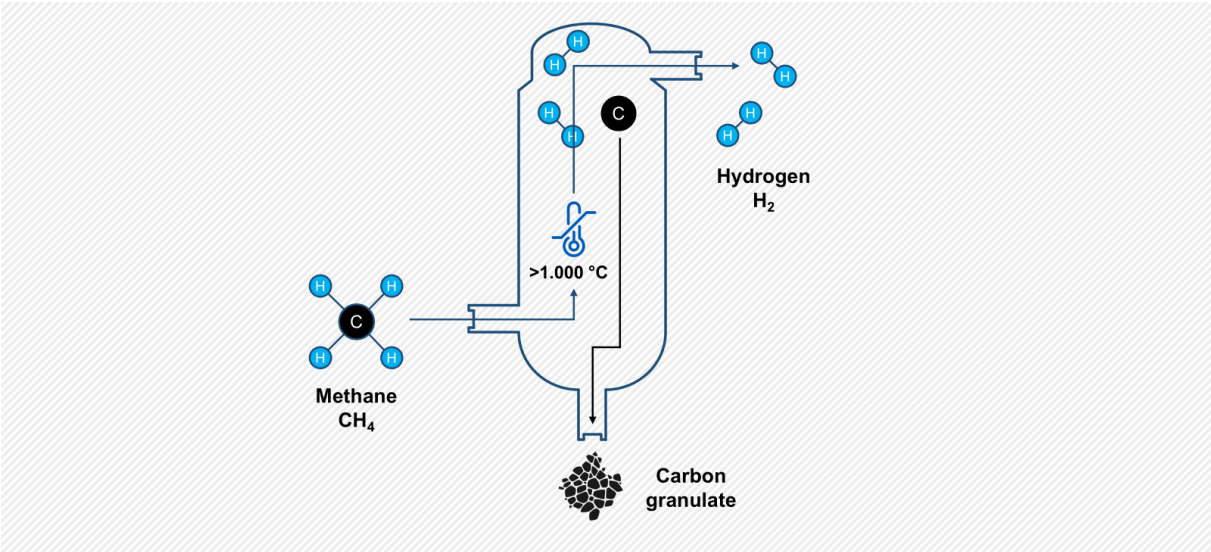
2.4 Hydrogen from methane pyrolysis ("turquoise hydrogen")

"Turquoise hydrogen" is produced by the (thermal) pyrolysis of natural gas, a high-temperature process (> 1,000 °C) in which methane (CH_4) is thermally decomposed into its components hydrogen and solid carbon in the absence of oxygen:

$$CH_4 \rightarrow 2\ H_2 + C$$

Provided that the solid carbon is permanently stored, the corresponding CO_2 emissions that would be associated with the oxidation of methane or solid carbon can be avoided. However, since the thermal energy in the selected process is generated by the combustion of natural gas, this data set still results in fossil CO_2 emissions. In principle, the hydrogen produced could also be used for this purpose. The solid carbon by-product can also be used in various industries, which could lead to the release of CO_2. The reactor diagram for the thermal pyrolysis of methane is shown in Figure 3.
As with methane reforming, the environmental impacts of the extraction, processing and transport of the raw material natural gas, from which the methane for pyrolysis is obtained, will also be taken into account. This includes methane emissions from extraction and processing according to the IEA Methane Tracker (IEA 2022).

Figure 3: Reactor diagram for methane pyrolysis



Source: (Rosental et al. 2024)

Pyrolysis technology is currently in the stage of laboratory research. There are a few demonstration plants. The TRL is around 3-6 (Rosental et al. 2024). Table 8 shows a selection of the most important energy and material requirements, based on (Hermesmann and Müller 2022). In the source used, part of the natural gas (0.86 kg/kg H_2) is burned to generate energy. This produces CO_2, which is emitted into the atmosphere.

Table 8: Selected operating parameters for the production of 1 MJ LHV "turquoise" hydrogen.

Synthesis	Unit	Value
Natural gas requirement	Nm^3	0.054
Electricity demand (including compression H_2 to 30 bar)	kWh	0.027
CO_2 emissions into the air	kg	0.0155
Solid carbon	kg	0.027
Material requirements*		
Palladium	kg	7.04E-08
Copper	kg	4.69E-08
Low-alloy steel	kg	1.66E-05
High-alloy steel	kg	3.24E-06
Silicon	kg	5.15E-07
Tin	kg	2.15E-04
Silicon carbide (SiC)	kg	2.69E-08

*Hermesmann and Müller (2022) do not specify the production capacity of the plant, so the material requirements are shown in relation to 1 MJ H_2

Source: (Hermesmann and Müller 2022; Patel et al. 2024), density of natural gas: 0.735 kg/Nm^3

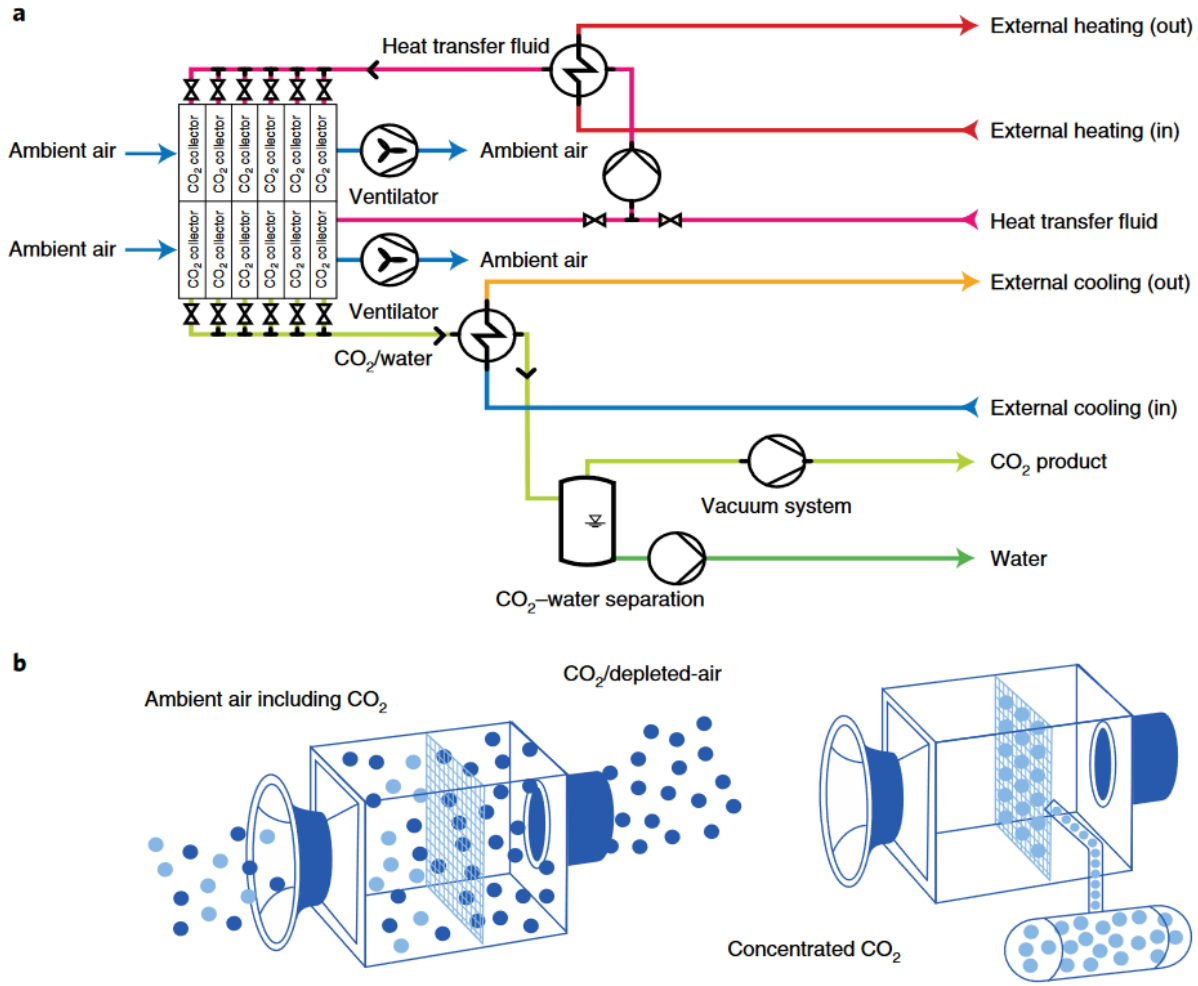
2.5 CO_2 sources

In order to construct the carbon skeleton of hydrocarbons, CO_2 is used as a carbon source in this study. In principle, various sources of CO_2 are conceivable, only some of which were considered in this project: in addition to the base case, i.e. capture from the air, only those CO_2 sources are examined that will continue to exist in a largely defossilised economic system and release concentrated CO_2. These are cement plants and waste incineration plants. Alternative building materials and waste avoidance are likely to reduce the amount of CO_2 available compared to today. However, an absolute assessment of potential is not part of this study.

Cement is produced in many industrialised countries and also in emerging economies. For the countries considered in this study, cement plants can be taken into account as a whole. Waste incineration plants are currently found to a significant extent mainly in Germany and other western industrialised countries. However, they also represent a desirable expansion option for waste treatment in other countries, which may promise higher potential in the future. Here, too, the quantities available in the future will depend on the specific design of a defossilised economic system (Münter et al. 2025).

In the base case, CO_2 is provided by direct air capture (DAC), as this option can be installed at any location independently of other infrastructure (except for energy supply). The global average concentration of CO_2 in the atmosphere is estimated at 419 ppm (0.0419 vol.%) for the year 2023 (Lan et al. 2025). Due to the low concentration, capturing CO_2 from the air is very energy-intensive because large volumes of gas have to be moved. The most promising and technically advanced processes currently work with an adsorptive coupling of CO_2 to a carrier material (highly branched polymer molecules with amino groups (N-H), e.g. polyethyleneimine PEI) at room temperature. Once the carrier is saturated, CO_2 is desorbed again under reduced pressure and at an elevated temperature (80-100 °C) (Deutz and Bardow 2021; Fröhlich et al. 2019; Qiu et al. 2022; Vocht et al. 2022).

Figure 4: Flow chart and adsorption/desorption phase of the DAC process from Climeworks.



a) Technical process flow diagram of DAC using a temperature-vacuum swing adsorption process with 12 CO_2 collectors, heat exchangers for heating and cooling, vacuum system and water separation unit. b) CO_2 collector in adsorption (left) and desorption phase (right). In the adsorption phase, the CO_2 (light blue) is bound to the adsorbents. In the desorption phase, the CO_2 is released by vacuum temperature change with the aid of heat below 100 °C. Source: (Deutz and Bardow 2021).

In **cement plants**, limestone is burned at temperatures of approx. 1,400-1,450 °C to produce calcium oxide (CaO), releasing CO_2. In addition to these process-related CO_2 emissions, which account for approximately two-thirds of a cement plant's total emissions, additional emissions are generated during the combustion of mostly fossil fuels in the rotary kiln (approximately one-third). In addition to primary energy sources such as coal, these fuels currently often consist of waste for recycling, e.g. waste plastics and old tyres. Due to the simultaneous release of CO_2 from limestone and fuel, the CO_2 concentration in the exhaust gas is comparatively high (approx. 14-33 vol.% CO_2). If the process were to be converted to hydrogen as a fuel in the course of the transformation of the energy system, this would result in lower CO_2 concentrations in the range of approx. 10-20 vol.%. The CO_2 can be removed from the exhaust gas stream by means of amine scrubbing. In this process, physically absorbed CO_2 reacts chemically with an amine contained in the scrubbing solution. This results in a significantly higher CO_2 concentration in the scrubbing solution and significantly increases selectivity. Common scrubbing solutions are mixed with monoethanolamine (MEA), diethanolamine (DEA) or methyldiethanolamine (MDEA), although many other amines are suitable for the scrubbing process (Puxty et al. 2009). The practical implementation takes place in a counter-current absorption column after prior desulphurisation

of the exhaust gas. Regeneration[3] takes place at 120–140 °C with the release of the bound CO_2. After cooling the amine solution to 40 °C, it is returned to the absorber (Fröhlich et al. 2019).

In the same way, CO_2 can be separated from the **exhaust gases of a waste incineration plant by means of amine scrubbing** after flue gas cleaning and condensation. The CO_2 concentration in the exhaust gas is slightly lower (12-15 vol.%), but due to the composition of the waste, a large proportion of biogenic carbon is contained. A biogenic CO_2 content of around 50% is usually assumed.

Biogas plants are generally available on a smaller scale and are only suitable for small-scale PtGLS production (Münter et al. 2025). Nevertheless, they can serve as a biogenic CO_2 source by means of **separation from biogas processing to biomethane**. Agricultural residues are particularly suitable as sustainable biomass sources. The CO_2 concentration in biogas is around 60 vol.%, and the CO_2 must be separated from the biomethane before it can be fed into the gas grid. This study models separation using amine scrubbing, which delivers a high CO_2 concentration without further processing. It is assumed that the electricity demand will be covered by German grid electricity and the heat demand by the combustion of biogas. The processing emissions are divided between biomethane and CO_2 according to carbon content; CO_2 does not receive any burdens from the biogas production itself.

The following potential CO_2 sources are not considered in this study:

- **Exhaust gases from the combustion of fossil fuels for energy production (power plant exhaust gases)** were not considered as CO_2 sources in this project. Since the combustion of fossil fuels can never be completely greenhouse gas neutral, this source is classified as unsustainable. In addition, the CO_2 emissions captured and stored in PtGLS products are released back into the atmosphere at the end of the PtGLS products' life cycle, meaning they do not contribute to a permanent reduction in CO_2 emissions.
- **Exhaust gases from the combustion of biogenic fuels for energy production** are excluded here, as today, in particular, cultivated biomass (wood) is used for energy production in biomass power plants. Cultivated biomass is considered problematic in some respects (land requirements and the associated changes in land use, as well as the use of fertilisers and pesticides, displacement of other uses, often monoculture) and further expansion of the use of cultivated biomass as an energy source is not desirable. The use of CO_2 from biogenic waste and residues and industrial biomass processes is dealt with in a separate short paper (Münter et al. 2025). The conclusion there is that, from a sustainability perspective, the only biogenic CO_2 sources that can be considered are the exhaust gases from waste incineration plants and pulp mills or biomethane processing (Münter et al. 2025).
- **Electrochemical extraction from seawater** (electrochemical direct ocean capture) is a technology currently being researched (Aleta et al. 2023; Karunarathne et al. 2025), but is not considered here due to its current low level of development (TRL 4-5).

Table 9 shows the most important operating parameters for the CO_2 sources considered in this study: direct air capture (DAC), cement plant, waste incineration plant (WIP) and biogas processing. The selected literature references consider not only the energy consumption of CO_2 capture itself, but also the production of sorbents and the facilities (Bisinella et al. 2021; Deutz and Bardow 2021; Meunier et al. 2020; Qiu et al. 2022). Details can be found in the separate technical appendix.

[3] According to information from the literature, approximately 3% of the heat in an integrated plant can be covered by waste heat from the cement plant, with the remainder being generated by additional combustion of fossil fuels.

Table 9: Selected operating parameters for the provision of 1 kg CO_2.

	Unit	DAC	Cement plant	Waste incineration WIP	Biogas processing
Separation rate	%	90	90	90	97
Share of installed systems on total biogas plants	%				53
Input					
Electricity	kWh	0.5	0.0069	0.1	0.11
Heat	MJ	5.4[3]	3.65[4]	1.72[5]	3.76
Amine	kg	0.003[1]	0.004[2]	0.004[2]	0.004[2]
Output					
CO_2	kg	1	1	1	1
Biomethane	m^3				0.98
Emissions into the air					
CO_2 fossil	kg	0	0.1034	0.0875	0
CO_2 biogenic	kg	0	0.0066	0.0875	0
Methane	kg	0	0	0	0.00041
Source		Deutz and Bardow 2021	Müller et al. 2024	Bisinella et al. 2021	Dunkelberg et al. 2015

[1] PEI on silica carrier with 36% PEI content by weight

[2] Monoethanolamine

[3] Heat demand is covered by waste heat from PtGLS synthesis

[4] Heat requirement for MEA scrubbing 3.76 MJ/kg CO_2, of which 0.11 MJ is covered by internal waste heat

[5] Heat requirement for MEA scrubbing 3.76 MJ/kg CO_2, of which 90% is covered by internal heat production, but 40% of this can no longer be fed into the district heating supply and must therefore be replaced

Source: (Bisinella et al. 2021; Deutz und Bardow 2021; FNR 2014; Müller et al. 2024; Qiu et al. 2022)

The same source that supplies the coupled synthesis plant is assumed to be used as electricity for capture from the air. The waste heat from the synthesis plant covers the heat demand of the DAC unit.

The electricity for capture in the cement plant and biogas processing is sourced from the site-specific electricity mix. The heat for amine scrubbing is provided by additional generation from fossil fuels. Electricity and heat from internal generation are used for CO_2 capture from the waste incineration plant. This reduces the amount of electricity fed into the grid and the amount of heat extracted, e.g. into heating networks.

The environmental impacts of manufacturing the capture equipment are also taken into account.

2.6 Ammonia synthesis

Ammonia synthesis is carried out using the Haber-Bosch process, which uses "green" (see section 2.2) hydrogen to produce "green" ammonia. The manufacturing processes are supplied

with the electricity mix of the respective location; other processes carried out in Germany are based on the national electricity mix.

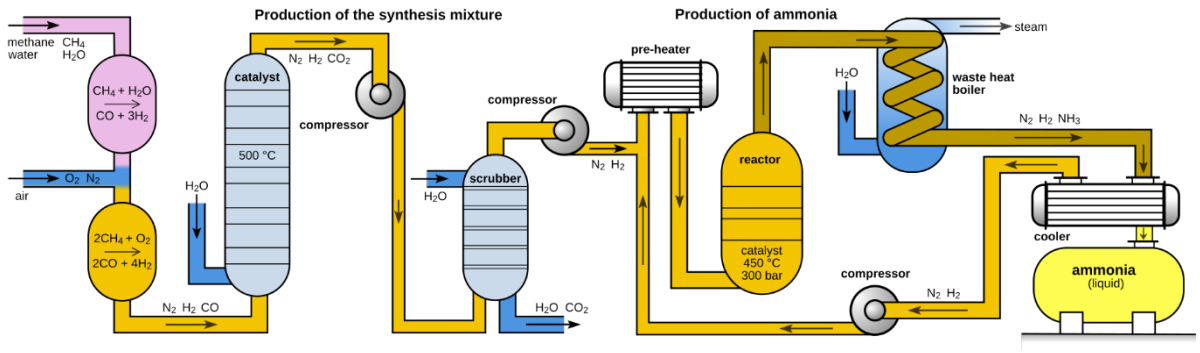
In the Haber-Bosch process, ammonia (NH_3) is produced from nitrogen (N_2) and hydrogen (H_2) according to the following reaction scheme:

$$N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3$$

The reaction takes place under high pressure (150-350 bar) and medium temperature (450-550°C) and is catalysed by iron.

In the conventional process, hydrogen is produced from the steam reforming of methane. Through partial combustion of the methane with air, the required nitrogen is added to the synthesis gas mixture, while the oxygen in the air is consumed. After the removal of water and CO_2 in the gas scrubbing process, the starting materials for ammonia synthesis, N_2 and H_2 remain (Figure 5).

Figure 5: Process diagram of large-scale ammonia synthesis according to Haber and Bosch.



Source: Wikipedia, 2007: Haber-Bosch process. Licence: CC-BY-SA 4.0. (https://en.wikipedia.org/wiki/Haber_process#/media/File:Haber-Bosch-En.svg)

When using green hydrogen, the nitrogen must be supplied separately from the air, either by cryogenic air separation or by pressure swing adsorption, the latter being suitable only for smaller plants. Cryogenic air separation requires approximately 0.3 kWh of electricity per kg of nitrogen (D'Angelo et al. 2021). Since both hydrogen and nitrogen are produced at low temperatures and pressures, the reaction mixture must be brought to the reaction conditions (see above) before entering the reactor.

The generic data set "chemical factory construction, organics" from the LCA database ecoinvent (ecoinvent 2024; Wernet et al. 2016) was used for the construction and dismantling of the plants (see also section 2.13).

Table 10: Selected operating parameters for the production of 1 kg of ammonia.

	Unit	Value
Input		
Hydrogen	kg	0.176
Nitrogen	kg	0.815
Electricity	kWh	0.556
Output		

	Unit	Value
Ammonia	kg	1
Emissions into the air		
Ammonia	kg	0.00163
Nitrogen oxides	kg	0.001

Source: (D'Angelo et al. 2021; Patel et al. 2024)

2.7 Ammonia splitting

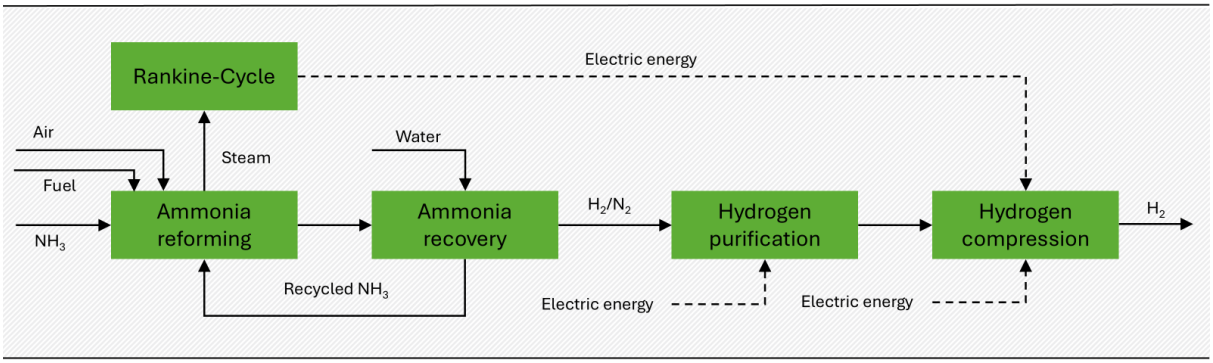
Ammonia can be used as a carrier substance for hydrogen. To do this, ammonia must be broken down into its constituent parts (a process known as ammonia cracking). The cracking process is highly endothermic and, together with the subsequent separation and purification of the hydrogen, requires thermal energy of approximately 4.7 MJ/kg NH_3 (corresponding to approximately 35 MJ/kg H_2) (Chatterjee et al. 2021; Jackson et al. 2020). Compressing the hydrogen to 250 bar requires approx. 1.8 kWh/kg H_2 electrical energy (Jackson et al. 2020). Jackson et al. (2020) describe a process for producing 200 t H_2 per day (see Figure 6), which includes the following steps:

- Ammonia cracking on iron/cobalt or nickel/aluminium oxide catalysts (Alghool et al. 2024; TOPSOE 2023) at 400-450 °C
- Separation of hydrogen and unreacted ammonia
- Recycling of unreacted ammonia to the reformer
- Separation of hydrogen and nitrogen by liquefaction
- Heat is generated by burning part of the ammonia used and part of the hydrogen produced. The excess steam is used to generate electricity via a turbine, which is used to compress the hydrogen.

Only 76% of the hydrogen bound in NH_3 is recovered. In terms of energy, this corresponds to an efficiency of 86%.

The generic data set "chemical factory construction, organics" from the ecoinvent LCA database (ecoinvent 2024; Wernet et al. 2016) was used for the construction and dismantling of the plants (see also section 2.13). Details can be found in the Excel table in the separate technical appendix.

Figure 6: Process flow diagram for ammonia-splitting.



Source: own representation, ifeu, based on (Jackson et al.2020).

Table 11: Selected operating parameters for the splitting of ammonia to produce 1 kg of hydrogen.

	Unit	Value	Source
Input			
Ammonia	kg	7.46	Derived from Jackson et al. 2020
Electricity	kWh	4.82	Derived from Jackson et al. 2020
Al_2O_3 (catalyst carrier)	kg	5.11E-05	Alghool et al. 2024
Nickel (catalyst)	kg	5.11E-05	Alghool et al. 2024
Cooling water	kg	0.0383	Alghool et al. 2024
Output			
Hydrogen	kg	1	
Emissions into the air			
Ammonia	kg	0.00746	Estimate: 0.1% slip
Nitrogen oxides	kg	0.00746	Estimate: 0.1% oxidation

Source: (Alghool et al. 2024; Jackson et al. 2020)

Despite thorough literature research and expert discussions, no reported data on direct emissions from ammonia splitting could be found. Since no fossil fuels are used in the process itself, emissions of CO, CO_2, NMVOC, and SO_2 are excluded. The formation of NO_X in the reactor is also reduced by the absence of oxygen. To map direct emissions after exhaust gas purification by selective catalytic reduction (SCR), an ammonia slip and a residual oxidation of 0.1% per kg of ammonia used were therefore estimated (Table 11).

When using ammonia as an energy carrier or hydrogen carrier, it must be taken into account that ammonia can be emitted during loading, storage and transport. These processes are usually carried out with liquefied ammonia at -34°C. During storage and transport, cooling is achieved by allowing part of the ammonia to evaporate, with the evaporative cooling keeping the temperature stable. Some of the evaporated ammonia (boil-off gas, BOG) is liquefied again and returned, but some also escapes into the atmosphere.

Table 12: Loss rates during loading, storage and transport of ammonia.

	Losses	Comment
Loading processes	0.037	Per loading and unloading process (ship)
Storage	0.02	Due to leaks (storage over 20 days)
Transport	0.025% / day	Transport times range from 20 to 50 days

Source: (de Kleijne et al. 2024)

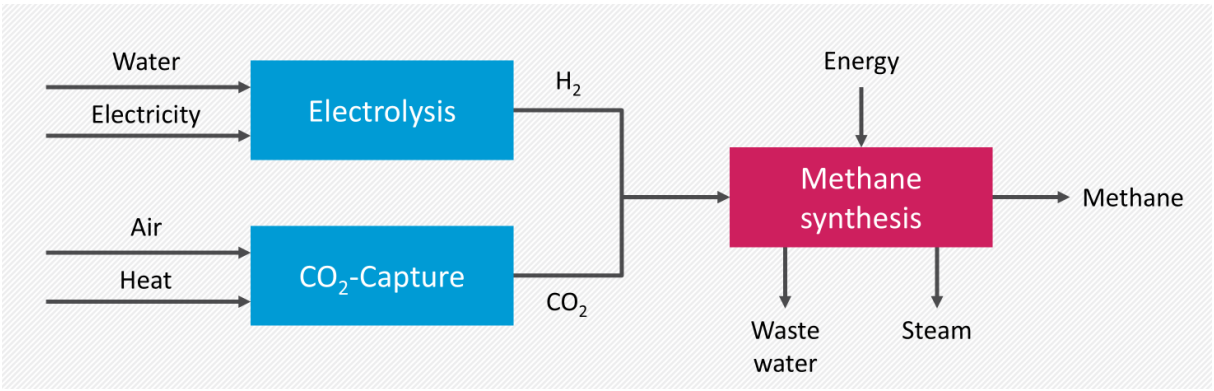
2.8 Methane synthesis

In power-to-gas synthesis (PtG), methane is synthesised from CO_2 and hydrogen in a single step, the Sabatier process, and then treated in a gas drying unit. Since the product, similar to natural gas, may still contain small amounts of CO_2 and hydrogen, it is also called synthetic natural gas (SNG). The exothermic reaction proceeds according to the following scheme:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

Typical process conditions are 300-550 °C, moderate pressures (5-10 bar) and require the presence of a nickel catalyst. Water is condensed out of the product gas and the methane is separated by processing further by-products (primarily CO and unreacted CO_2). Various reactor designs are available for the reaction, for example two-phase fixed and fluidised bed reactors, (micro-)structured reactors and three-phase fluidised bed reactors (Rönsch et al. 2016).

Figure 7: Process diagram of methane synthesis.



Source: Own representation, ifeu.

A simplified data set consisting of stainless steel and polyethylene, as well as a Ni/Al_2O_3 catalyst, was used for the construction and dismantling of the plants, as specified in the literature source used (Zhang et al. 2017). Details can be found in the Excel table in the separate technical appendix.

Table 13: Selected operating parameters for methane synthesis.

	Unit		Source
Input			
CO_2	kg	2.94	Navajas et al. 2022
Hydrogen	kg	0.51	Navajas et al. 2022

	Unit		Source
Electricity demand	kWh	0.33	Navajas et al. 2022
Nickel (catalyst)	kg	1.6 E-05	Navajas et al. 2022
Output			
Methane	kg	1	
Thermal energy	kWh	3.01	Navajas et al. 2022
Emissions into the air			
CO_2	kg	0.19	Navajas et al. 2022

Source: (Navajas et al. 2022; Zhang et al. 2017, 2020)

2.9 Methanol synthesis

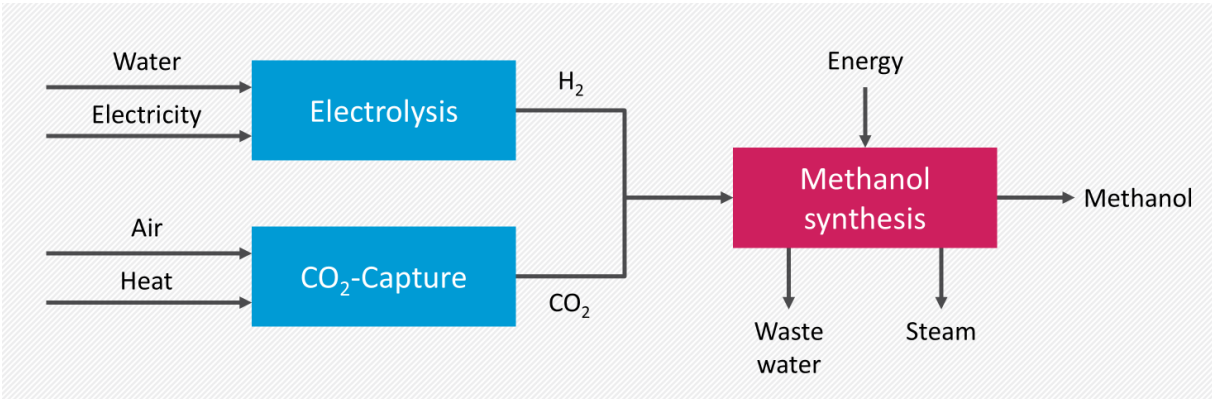
The synthesis of methanol from carbon dioxide and hydrogen proceeds according to the following exothermic reaction equation:

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$$

In principle, there are two options available for purely electricity-based process control (Rosental et al. 2024):

- In the two-stage synthesis, CO_2 is first converted with hydrogen to CO and water (reverse water-gas shift reaction, RWGS). For the synthesis to methanol, CO and water are separated from each other and CO is fed into the reactor together with a hydrogen stream. The reaction takes place at 50–100 bar and 200–300 °C on copper/zinc oxide catalysts (Lange 2001). After the reaction, unreacted gas is recycled, a small portion is burned as purge gas, and excess heat is recovered. Unwanted by-products and water are separated by distillation to obtain pure methanol (Bazzanella and Ausfelder 2017). For modelling purposes, it is assumed that excess heat energy is used for CO_2 capture.
- In direct synthesis, CO_2 and H_2 are fed together into the reactor, where they react to form methanol and water. Compared to two-stage synthesis, the reaction conditions are milder and heat dissipation is lower. This means that cooling is less complex and fewer by-products are produced, resulting in a higher yield (Marlin et al. 2018).

Figure 8: Process diagram of direct methanol synthesis.



Source: Own representation, ifeu.

The further calculations in this study are based on single-stage methanol synthesis, as this has already been implemented in pilot and industrial plants (TRL 7-9) In Table 14, the process parameters for single-stage methanol synthesis are presented, based on the work of Hank et al. (2019) and Schemme (2020). For the construction and dismantling of the plants, the generic data set "chemical factory construction, organics" from the LCA database ecoinvent (ecoinvent 2024; Wernet et al. 2016) was used, supplemented by a list of materials proposed by the authors mentioned above, which also includes a $Zn/Cu/Al_2O_3$ catalyst. Details can be found in the Excel table in the separate technical appendix.

Table 14: Selected operating parameters for single-stage methanol synthesis.

	Unit		Source
Input			
CO_2	kg	1.37	Schemme 2020
Hydrogen	kg	0.19	Schemme 2020
Cooling water	kg	68.8	Hank 2019
Electricity	kWh	0.154	Schemme 2020
Copper oxide	kg	7.9E-06	Hank 2019
Zinc oxide	kg	2.1E-05	Hank 2019
Aluminium oxide	kg	4.0E-06	Hank 2019
Output			
Methanol	kg	1	
Excess steam	MJ	1.76	Schemme 2020
Water	kg	0.6	Own calculation
Cooling water	kg	68.8	Hank 2019

Source: (Hank et al. 2019; Schemme 2020)

2.10 Methanol-to-gasoline

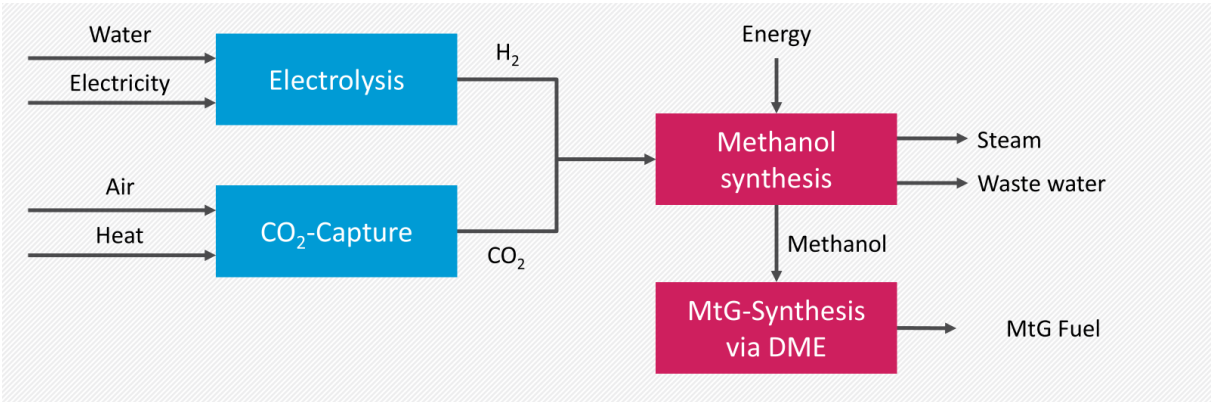
In a synthesis reactor, methanol is converted into petrol via the intermediate product dimethyl ether (DME) using a catalyst (e.g. Cu/ZnO). In a second step, this must be separated from residual methanol. The MtG technology has already been tested in practice and used in various demonstration and industrial production plants. A plant already existed in New Zealand in the 1990s. An MtG plant is currently under construction in Chile (Haru Oni), which is scheduled to produce 410,000 tonnes per annum from 2026. However, current production capacity is only just under 100 tonnes of petrol per year[4], supplied with biogenic CO_2 from a nearby brewery. The installation of a direct air capture plant to supply CO_2 is expected to be completed in 2025[5]. The process data used in the model comes from Chemieanlagenbau Chemnitz GmbH and was collected in a FVV study by the German Industrial Research Association for

[4] https://www.hifglobal.com/locations/hif-haru-oni (26 June 2025)

[5] https://www.hifglobal.com/media/news-description/2024/12/12/02-hif-global-begins-installation-of-the-first-direct-air-capture-unit-in-chile (26 June 2025)

Energy Conversion Systems FVV (Kramer et al. 2022). The efficiency in terms of calorific value (petrol production relative to methanol input) is 82%.

Figure 9: Process diagram of MtG synthesis.



Source: Own representation, ifeu.

For the construction and dismantling of the plants, the generic data set "chemical factory construction, organics" from the LCA database ecoinvent (ecoinvent 2024; Wernet et al. 2016) was used, supplemented by a list of materials proposed by (Schemme 2020). Details can be found in the Excel table in the separate technical appendix.

Table 15: Selected operating parameters for petrol production using the methanol-to-gasoline process.

	Unit	Value	Source
Input			
Methanol	kg	2.67	Kramer et al. 2022
Electricity	kWh	0.046	Schemme 2020
Output			
Petrol	kg	1	
Excess steam	MJ	2.94	Schemme 2020
Water as a by-product	kg	1.23	Schemme 2020

Source: (Kramer et al. 2022; Schemme 2020)

2.11 Dimethyl ether synthesis

Dimethyl ether is produced by catalytic condensation of methanol with the release of water according to the following reaction scheme:

$$2\ CH_3OH \rightarrow CH_3OCH_3 + H_2O$$

The reaction on an aluminium catalyst is highly selective, i.e. virtually no by-products are formed. As a result, the efficiency of the reaction in terms of calorific value is almost 100%.

The generic data set "chemical factory construction, organics" from the LCA database ecoinvent (ecoinvent 2024; Wernet et al. 2016) was used for the construction and dismantling of the

plants, supplemented by a list of materials proposed by (Schemme 2020). Details can be found in the Excel table in the separate technical appendix.

Table 16: Selected operating parameters for the production of dimethyl ether (DME).

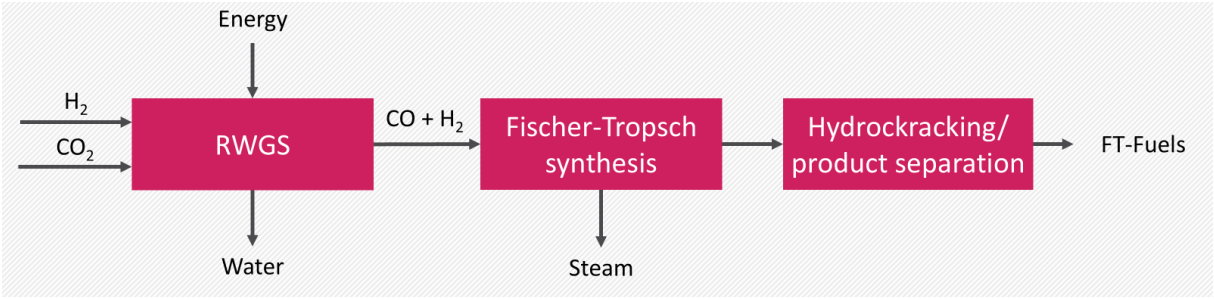
	Unit	Value	Source
Input			
Methanol	kg	1.43	(Schemme 2020)
Electricity	kWh	0.0014	(Schemme 2020)
Steam	MJ	1.946	(Schemme 2020)
Output			
DME	kg	1	
Excess steam	MJ	0.571	(Schemme 2020)
Water as a by-product	kg	0.391	(Schemme 2020)

Source: (Schemme 2020)

2.12 Fischer-Tropsch synthesis

In Fischer-Tropsch synthesis, long-chain hydrocarbons are assembled from the simple building blocks hydrogen and CO_2. In a first step, CO_2 and H_2 are used in a reverse water gas shift (RWGS) reaction to produce synthesis gas, a mixture of CO and H_2. The synthesis gas is converted at temperatures of 210–340°C over iron and cobalt catalysts into a mixture of long-chain hydrocarbons (Rosental et al. 2024). The composition of the synthesis products varies depending on the reaction conditions, reactor type and synthesis gas mixture ratio ($CO:H_2$= 1:2 to 1:20). The reaction heat released can be utilised by integrating it into other processes.

Figure 10: Process diagram of Fischer-Tropsch synthesis via RWGS.

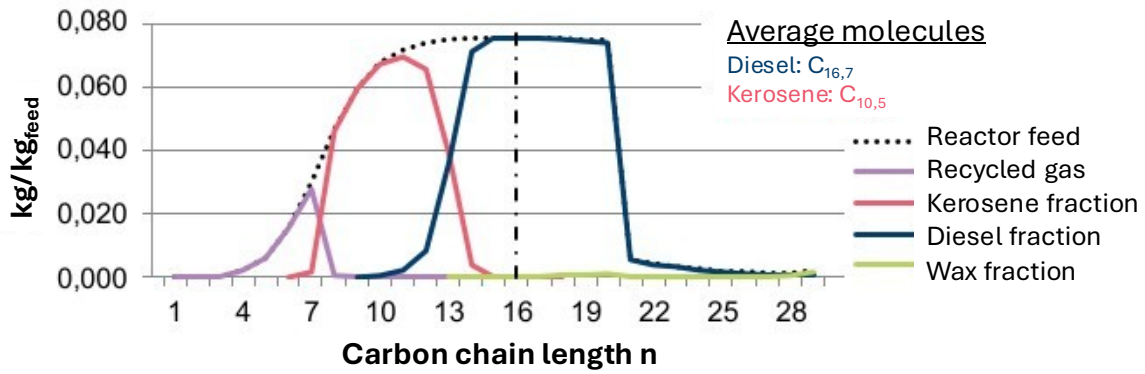


Source: Own representation, ifeu.

The Fischer-Tropsch synthesis primarily yields long-chain hydrocarbons, producing mainly petrol, kerosene and diesel. In an exemplary mass balance from (Schemme 2020), this corresponds to a product quantity of approximately 19% by weight (each carbon chain length with a proportion between 0.2% and 0.6%). At the same time, 40% by weight of water is produced as waste. Part of the CO used is oxidised to CO_2 during the reaction (24% by weight) and another part of the CO (10% by weight) is not converted. By-products include methane (5.5 wt%) and waxes/heavy oils with a chain length of more than 48 carbon atoms (approx. 2.0 wt%). The product distribution is shown in Figure 1. The gas product is fed to the reformer and the wax to a hydrocracker, leaving only kerosene and diesel as products. The chain growth

probability and thus the product distribution can be shifted towards the kerosene or diesel fraction via the H_2/CO ratio, the catalyst composition and the temperature (Schemme 2020). The burdens of the FT process and downstream refining are allocated according to the calorific value of the products (and the quantities produced) (section 4.1.3).

Figure 11: Product distribution of atmospheric distillation in the FT process



Source: (Schemme 2020)

The crude product is usually refined in a hydrocracker and a product processing/refining unit. Since the synthesis results in a broad product distribution and the petrol, diesel and kerosene fractions are separated from each other after synthesis by product processing, all three energy sources are evaluated together in this study with the same production effort. The most important operating parameters of Fischer-Tropsch synthesis are shown in Table 17.

Direct emissions into the air from FT synthesis are mainly expected to result from the combustion of unreacted gases and by-products (CO, CO_2, NO_X, VOC, etc.), but these have not yet been quantified. No information is available on emissions into water (Rosental et al. 2024).

A simplified data set consisting of stainless steel, structural steel and concrete, as well as a Co/zeolite catalyst, was used for the construction and dismantling of the plants, as specified in the literature source used (Schemme 2020). Details can be found in the Excel table in the separate technical appendix.

Table 17: Selected operating parameters for the production of liquid energy sources via Fischer-Tropsch synthesis.

	Unit	Value	Source
Input			
CO_2	kg	3.14	Liebich et al. 2021
Hydrogen	kg	0.49	Kramer et al. 2021
Electricity	kWh	0.30	Schemme 2020
Process water	kg	3.73	Liebich et al. 2021
Cooling water	kg	161	Liebich et al. 2021
Output			
FT fuel	kg	1	

	Unit	Value	Source
Surplus steam	MJ	13.2	Assumption: Heat recovery 70%

Source:(Kramer et al. 2021; Liebich et al. 2021; Schemme 2020)

2.13 Production facilities and infrastructure

The construction and dismantling of the facilities for the production of PtGLS products were taken into account in the environmental impact assessment, as were the catalysts used. The material requirements were distributed over the total quantity of product manufactured over the lifetime of the facility. This is calculated by multiplying the lifetime, production capacity and operating hours per year. The description of the individual production facilities is too extensive to be included here, but the data can be found in the Excel table in the separate technical appendix. Table 18 provides an overview of the parameters assumed for determining lifetime production.

Large-scale plants for ammonia production and methane steam reforming are directly represented using the ecoinvent process "market for chemical factory, organics".

Table 18: Parameters for determining the lifetime production of the processes examined.

	Production capacity	Service life (a)	Operating hours per year (h/a)	Source
PEMEL electrolysis stack	1 MW_{el}	13.25	4,000	Smolinka et al. 2018
PEMEL electrolysis BoP	1 MW_{el}	21	4,000	Smolinka et al. 2018
AEL electrolysis stack	1 MW_{el}	17.5	4,000	Smolinka et al. 2018
AEL electrolysis BoP	1 MW_{el}	28	4,000	Smolinka et al. 2018
CO_2 Direct Air Capture System	100 kt CO_2 /a	20	4,000	Deutz and Bardow 2021
Methane reforming (SMR and ATR)	50 kt/a	50	8,000	
Methane pyrolysis	N/A	20	8,000	Hermesmann and Müller 2022
Methane synthesis plant	180 t CH_4 /a	20	8,000	Zhang et al. 2020
Methanol synthesis plant	50 kt/a	20	8,000	Hank et al. 2019
MtG plant	50 kt/a	20	8,000	Hank et al. 2019
DME	50 kt/a	20	8,000	Hank et al. 2019
FT plant	600 kt/a	20	8,000	Van der Giesen et al. 2014

N/A: not available

Source: (Deutz and Bardow 2021; van der Giesen et al. 2014; Hank et al. 2019; Hermesmann and Müller 2022; Smolinka et al. 2018; Zhang et al. 2020)

For electrolysers, it is assumed that their service life will develop over the coming years. The assumptions regarding the service life of stacks and electrolyser systems are presented in Table

19 and Table 20. The values are based on (Smolinka et al. 2018) and assume 4,000 full-load hours for electrolysis per year.

Table 19: Lifetimes of the modelled electrolysis technologies, stack.

Electrolysis technology		Stack service life [1,000 hours]		
	Year	2017	2025	2030
Alkaline electrolysis		56	70	80
Polymer electrolyte membrane electrolysis		44	53	60

Source: derived from (Smolinka et al. 2018)

Table 20: Lifetimes of modelled electrolysis technologies, system.

Electrolysis technology		System lifespan [years]		
	Year	2017	2025	2030
Alkaline electrolysis		27	28	29
Polymer electrolyte membrane electrolysis		20	21	22

Source: derived from (Smolinka et al. 2018)

2.14 Transport

Transport processes are powered by fossil fuels. This corresponds to the current state of the art. The use of the transported PtGLS products as fuel is discussed in the target scenarios in Section 5.

The following options are assumed for the transport of PtGLS products from non-European countries to Germany:

- Liquid and liquefied energy carriers (synthetic petrol, diesel, DME, methanol, ammonia) are transported by tanker. In the case of ammonia, a loss of 0.025% per day due to boil-off gas is assumed (de Kleijne et al. 2024), which is emitted into the atmosphere, as there are currently no NH_3-powered ships on the market.
- Synthetic natural gas is transported by pipeline, provided that pipelines exist or are planned (950 mm diameter, 10 mm wall thickness, service life 40 years). Alternatively, liquefied transport by ship is assumed, similar to today's liquefied gas transports. In this case, a methane slip in the engine of 1-3% of the fuel is assumed, which is emitted into the atmosphere.
- As a standard method for transporting hydrogen, this study assumes that ammonia is used as a hydrogen carrier, provided that there is no hydrogen pipeline on the transport route. In this case, ammonia synthesis (see section 2.6), ammonia transport (see above) and ammonia splitting (see section 2.7) are taken into account. The following alternatives are examined:
  - Hydrogen pipeline for short to medium distances (up to 3,000 km). The compressors are powered by grid electricity (compressors every 125 km, 0.3 kWh/kg H_2 each). The power supply is provided by the electricity mix of the country of production. Data for the

H_2 pipeline are: 1220 mm diameter, wall thickness 30 mm, service life 40 years (Tsiklios et al. 2022).

- Transport of liquefied hydrogen by ship. In this case, the ship is powered by boil-off gas.
- Transport of the liquid hydrogen carrier LOHC (Liquid Organic Hydrogen Carrier) by ship with return transport of the "empty" LOHC (Cho et al. 2024; Wulf et al. 2018).
- Transport of the liquid hydrogen carrier dimethyl ether by ship with return transport of CO_2 (with liquefaction of CO_2, assuming 3% CO_2 loss).

The hydrogen content in these carrier substances varies considerably: LOHC contains 6.2% by weight of H_2, NH_3 contains 17.6% by weight of H_2, DME contains 26.1% by weight of H_2. This affects the transport emissions per kilogram of H_2.

2.15 Water treatment

The water requirements for the individual process steps are shown in the respective process descriptions. In principle, the generic data set "market for water, deionised" from the ecoinvent database (ecoinvent 2024; Wernet et al. 2016) was used for the provision of process water. This describes the provision of fully deionised water with a conductivity of 0.1-1 µS/cm^2 from groundwater and surface water. The electricity requirement is approximately 0.03 kWh/m^3.

For seawater desalination, the ecoinvent process "tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage" is used, which assumes an electricity requirement of approx. 3.7 kWh/m^3 and also contains emission data for the concentrated permeate solution.

2.16 CO_2 storage including compression and transport

If hydrogen is obtained from the steam reforming of natural gas (section 2.3), the CO_2 produced in the process is captured, liquefied, transported to a suitable storage location and injected into deep rock layers. This study considers two options as examples:

- capture at the plant, transport via CO_2 pipeline over a distance of 200 km and injection at a depth of 1,000 m in a saline aquifer.
- capture at the plant, transport by ship over a distance of 50 km and injection into a former gas storage site.

The process data for liquefaction, transport via CO_2 pipeline and injection are taken from Volkart et al. (2013). This also includes the emissions related to infrastructure (pumps, turbines, tanks for liquefaction; construction and maintenance of the CO_2 pipeline; borehole and compressors for injection). The emission data for ship transport are taken from Roussanaly et al. (2021) and also include the construction and maintenance of the ship.

2.17 Additional facilities

Operating data for the following additional processes are included in the modelling and are provided in detail in an Excel table as a separate appendix.

- Liquefaction of methane
  - Power requirement for liquefaction 0.08 kWh/kg SNG

- Energy requirement for methane combustion in gas turbine: 5.2 MJ/kg SNG for liquefaction, 0.25 MJ/kg SNG for regasification
- Methane loss: 0.05%

► Liquefaction and regasification of hydrogen:

- Electricity requirement: 8.5 kWh/kg H_2 for liquefaction, 0.75 kWh/kg H_2 for regasification
- Hydrogen loss: 7.1%

► Liquefaction of ammonia:

- Power requirement for liquefaction and loading: 0.08 kWh/kg NH_3 (de Kleijne 2024)

3 Process chains for the production of PtGLS products

In this project, a base path is defined for each of the PtGLS products under investigation, which currently represents a realistic combination of production location, electricity source, synthesis technology and transport method. In addition, variants of the base paths are being investigated to illustrate the influence of various parameters on environmental impacts, further possible developments and, in some cases, extreme cases of PtGLS product process chains. The process chains and their variations are presented in detail in the following sections. An overview of all variants is listed in Table 21.

The base cases describe the production of PtGLS products hydrogen, ammonia, SNG, methanol, dimethyl ether and fuels (generally "FT") in the MENA region using hydrogen from alkaline electrolysis and electricity from renewable energies. Any CO_2 required is obtained from DAC and the end products are transported to Germany. The transport and (if necessary) conversion of H_2 carriers back to hydrogen is carried out using conventional techniques (e.g. tankers powered by fossil fuels) and grid electricity (e.g. for ammonia splitting).

Variations were made (*base cases in italics*)

- Transport distance (400 km, 2,000 km, *4,000 km*, 10,000 km, 19,000 km)
- Transport method (*ship*, pipeline)
- Hydrogen carrier/state for transport (gaseous, liquefied, *ammonia*, LOHC, DME)
- Power source for electrolysis (*RE mix*, supply mix grid electricity, 100% wind, 100% PV, 100% CSP), including power storage
- Hydrogen production method (*AEL*, PEMEL, SMR+CCS, ATR+CCS, methane pyrolysis)
- Ammonia production method (with *green H_2*, with blue H_2)
- Production method for liquid hydrocarbons (*FT synthesis*, methanol, DME, methanol-to-gasoline)
- CO_2 source (*direct air capture*, waste incineration plant, cement plant, from biomethane processing)
- Locations (*MENA region*, Germany, Australia, Chile, USA, Canada, South Africa, Spain, Denmark)

All base cases and variants are given a sequential number and a short description of the relevant parameters to ensure that the results graphs are easy to read.

Example of how to read the variant designations

- "B-01: H_2, MENA, RE mix, AEL, NH_3, ship & splitting": Describes the production of hydrogen with location-specific RE electricity mix in the base case in the MENA region, the synthesis and transport via ammonia in ships and the subsequent conversion back into hydrogen through ammonia splitting in Germany.
- "V-09: H_2, DE, RE electricity DE, GH_2, pipeline": Describes the production of hydrogen in variant 09 in Germany, using site-specific RE electricity mix and transport as gaseous hydrogen in a pipeline network over a distance of 400 km.

An overview of all variants is listed in Table 21. Base cases and variants were defined in such a way that the widest possible range of technological combinations and supply chains could be represented. Both "minimum" and "maximum" variants were mapped based on findings from previous projects (Biemann et al. 2024; Dittrich et al. 2025; Liebich et al. 2021), as well as politically relevant paths based on international agreements.

Table 21: Overview of provisioning paths for PtGLS products.

No.	Type	Product	Location	Electricity	Process	CO_2	PtGLS synthesis/ H_2 carrier	Transport	Abbreviation
B-01	Base case "status quo"	H_2	MENA	RE mix	AEL	-	NH_3	Ship & splitting	B-01: H_2, MENA, RE mix, AEL, NH_3, ship & split
B-02	Base case "status quo"	NH_3	MENA	RE mix	AEL	-	NH_3	Ship	B-02: NH_3, MENA, RE mix, AEL, NH_3, ship
B-03	Base case "status quo"	SNG	MENA	RE mix	AEL	DAC	SNG	LNG Ship	B-03: SNG, MENA, RE mix, AEL, DAC, SNG, LNG ship
B-04	Base case "status quo"	MeOH	MENA	RE mix	AEL	DAC	MeOH	Ship	B-04: MeOH, MENA, RE mix, AEL, DAC, MeOH, ship
B-05	Base case "status quo"	DME	MENA	RE mix	AEL	DAC	DME	Ship	B-05: DME, MENA, RE mix, AEL, DAC, DME, ship
B-06	Base case "status quo"	FT	MENA	RE mix	AEL	DAC	FT	Ship	B-06: FT, MENA, RE mix, AEL, DAC, FT, ship
V-07	Variant	H_2	MENA	grid mix	SMR + CCS	-	NH_3	Ship & splitting	V-07: H_2, MENA, grid mix, SMR + CCS, NH_3, Ship & Split
V-08	Variant	H_2	MENA	grid mix	Pyrolysis	-	NH_3	Ship & splitting	V-08: H_2, MENA, grid mix, pyrolysis, NH_3, ship & splitting
V-09	Variant	H_2	DE	RE mix	AEL	-	GH_2	Pipeline	V-09: H_2, DE, RE mix, AEL, GH_2, pipeline
V-10	Variant	H_2	MENA	RE mix	AEL	-	GH_2	Pipeline	V-10: H_2, MENA, RE mix, AEL, GH_2, pipeline
V-11	Variant	H_2	MENA	RE mix	AEL	-	LH_2	Ship & Regasification	V-11: H_2, MENA, RE mix, AEL, LH_2, ship & regasification

No.	Type	Product	Location	Electricity	Process	CO_2	PtGLS synthesis/ H_2 carrier	Transport	Abbreviation
V-12	Variant	H_2	MENA	RE mix	AEL	-	LOHC	Ship & splitting	V-12: H_2, MENA, RE mix, AEL, LOHC, ship & splitting
V-13	Variant	H_2	MENA	RE mix	AEL	-	DME	Ship & Split	V-13: H_2, MENA, RE Mix, AEL, DME, Ship & Split
V-14	Variant	H_2	MENA	grid mix	AEL	-	NH_3	Ship & Split	V-14: H_2, MENA, grid mix, AEL, NH_3, Ship & Split
V-15	Variant	H_2	MENA	PV	AEL	-	NH_3	Ship & splitting	V-15: H_2, MENA, PV, AEL, NH_3, Ship & Split
V-16	Variant	H_2	MENA	CSP	AEL	-	NH_3	Ship & Fission	V-16: H_2, MENA, CSP, AEL, NH_3, Ship & Split
V-17	Variant	H_2	MENA	Wind coastal	AEL	-	NH_3	Ship & splitting	V-17: H_2, MENA, Wind coastal, AEL, NH_3, Ship & Split
V-18	Variant	H_2	MENA	RE + storage	AEL	-	NH_3	Ship & splitting	V-18: H_2, MENA, RE+storage, AEL, NH_3, ship & splitting
V-19	Variant	H_2	MENA	RE mix	ATR + CCS	-	NH_3	Ship & splitting	V-19: H_2, MENA, RE mix, ATR + CCS, NH_3, ship & split
V-20	Variant	H_2	MENA	RE mix	PEMEL	-	NH_3	Ship & splitting	V-20: H_2, MENA, RE mix, PEMEL, NH_3, ship & splitting
V-21	Variant	H_2	MENA	RE mix	AEL	-	RE-NH_3	Ship & splitting	V-21: H_2, MENA, RE Mix, AEL, RE-NH_3, Ship & Split
V-22	Variant	NH_3	DE	RE mix	AEL	-	NH_3	Truck	V-22: NH_3, DE, RE mix, AEL, NH_3, truck
V-23	Variant	SNG	DE	RE mix	AEL	DAC	SNG	-	V-23, SNG, DE, RE power DE

No.	Type	Product	Location	Electricity	Process	CO_2	PtGLS synthesis/ H_2 carrier	Transport	Abbreviation
V-24	Variant	SNG	DE	RE mix	AEL	Bio-methane	SNG	-	V-24, SNG, DE, RE electricity DE, biomethane
V-25	Variant	SNG	MENA	RE mix	AEL	DAC	SNG	Pipeline	V-25, SNG, MENA, Pipeline
V-26	Variant	SNG	AU	RE mix	AEL	DAC	SNG	LNG Ship	V-26, SNG, AU, RE electricity AU, LNG ship
V-27	Variant	MeOH	DE	RE mix	AEL	DAC	MeOH	Truck	V-27, MeOH, DE, RE electricity DE, truck
V-28	Variant	MeOH	AU	RE mix	AEL	DAC	MeOH	Ship	V-28, MeOH, AU, RE electricity AU, ship
V-29	Variant	DME	DE	RE mix	AEL	DAC	DME	Truck	V-29, DME, DE, RE electricity DE, truck
V-30	Variant	DME	AU	RE mix	AEL	DAC	DME	Ship	V-30, DME, AU, RE electricity AU, ship
V-31	Variant	FT	MENA	grid mix	AEL	DAC	FT	Ship	V-31: FT, MENA, grid mix, AEL, DAC, FT, Ship
V-32	Variant	FT	MENA	PV	AEL	DAC	FT	Ship	V-32: FT, MENA, PV, AEL, DAC, FT, Ship
V-33	Variant	FT	MENA	CSP	AEL	DAC	FT	Ship	V-33: FT, MENA, CSP, AEL, DAC, FT, Ship
V-34	Variant	FT	MENA	Wind coastal	AEL	DAC	FT	Ship	V-34: FT, MENA, Wind coastal, AEL, DAC, FT, Ship
V-35	Variant	FT	MENA	RE + storage	AEL	DAC	FT	Ship	V-35: FT, MENA, RE+storage, AEL, DAC, FT, ship

No.	Type	Product	Location	Electricity	Process	CO_2	PtGLS synthesis/ H_2 carrier	Transport	Abbreviation
V-36	Variant	FT	MENA	RE mix	AEL	Cement	FT	Ship	V-36: FT, MENA, RE Mix, AEL, Cement, FT, Ship
V-37	Variant	FT	MENA	RE mix	AEL	MVA	FT	Ship	V-37: FT, MENA, RE mix, AEL, MVA, FT, ship
V-38	Variant	MtG	MENA	RE mix	AEL	DAC	MtG	Ship	V-38: MtG, MENA, RE Mix, AEL, DAC, MtG, Ship
V-39*	Variant	MeOH	ZA	Wind coastal	AEL	DAC	MeOH	Ship	V-39: MeOH, ZA, Wind coastal, AEL, DAC, MeOH, Ship
V-40*	Variant	MeOH	ZA	PV	AEL	DAC	MeOH	Ship	V-40: MeOH, ZA, PV, AEL, DAC, MeOH, ship
V-41*	Variant	H_2	DK	Wind coastal	AEL	-	GH_2	Pipeline	V-41: H_2, DK, Wind coastal, AEL, GH_2, Pipeline
V-42*	Variant	H_2	SP	PV	AEL	-	GH_2	Pipeline	V-42: H_2, SP, PV, AEL, GH_2, Pipeline
V-43*	Variant	H_2	SP	Wind coastal	AEL	-	GH_2	Pipeline	V-43: H_2, SP, Wind coastal, AEL, GH_2, Pipeline
V-44*	Variant	FT	ZA	PV	AEL	DAC	FT	Ship	V-44: FT, ZA, PV, AEL, DAC, FT, Ship
V-45*	Variant	SNG	CA	Wind coastal	AEL	DAC	SNG	LNG ship	V-45: SNG, CA, Wind coastal, AEL, DAC, SNG, LNG Ship
V-46	Variant	H_2	DE	grid mix	ATR + CCS	-	NG from US	NG via LNG ship -	V-46: H_2, DE, grid mix, ATR + CCS, NG from US
V-47	Variant	H_2	DE	grid mix	ATR + CCS	-	NG from NO	NG via pipeline	V-47: H_2, DE, grid mix, ATR + CCS, NG from NO

No.	Type	Product	Location	Electricity	Process	CO_2	PtGLS synthesis/ H_2 carrier	Transport	Abbreviation
V-48	Variant	H_2	DE	grid mix	ATR + CCS	-	NG from QA	NG by LNG ship	V-48: H_2, DE, grid mix, ATR + CCS, NG from QA
V-49*	Variant	MeOH	CL	Wind coastal	AEL	DAC	MeOH	Ship	V-49: MeOH, CL, Wind coastal, AEL, DAC, MeOH, Ship
V-50*	Variant	MeOH	CL	PV	AEL	DAC	MeOH	Ship	V-50: MeOH, CL, PV, AEL, DAC, MeOH, ship
V-51*	Variant	FT	AU	Wind coastal	AEL	DAC	FT	Ship	V-51: FT, AU, Wind coastal, AEL, DAC, FT, Ship
V-52*	Variant	FT	AU	PV	AEL	DAC	FT	Ship	V-52: FT, AU, PV, AEL, DAC, FT, Ship
V-53*	Variant	SNG	USA	Wind coastal	AEL	DAC	SNG	Ship	V-53: SNG, USA, Wind coastal, AEL, DAC, SNG, Ship
V-54*	Variant	SNG	USA	PV	AEL	DAC	SNG	Ship	V-54: SNG, USA, PV, AEL, DAC, SNG, Ship
V-55	Variant	H_2	DE	grid mix	SMR + CCS	-	NG from QA	-	V-55: H_2, DE, grid mix, SMR + CCS, NG from QA
V-56	Variant	H_2	DE	grid mix	Pyrolysis	-	NG from QA	-	V-56: H_2, DE, grid mix, pyrolysis, NG from QA

* Marked paths shown in the appendix only. Source: Own representation, ifeu

3.1 Hydrogen

In the base case for hydrogen production and delivery, green hydrogen production is assumed to take place in the Middle East and North Africa (MENA) region. The hydrogen is produced by alkaline electrolysis (AEL) using renewable electricity (RE), converted into ammonia (NH_3) and transported by ship over a distance of 4,000 km. After the cracking of ammonia in Germany, the green hydrogen is available for use. The top supply path shown and the other light green processes in Figure 12 refer to the base case.

- **Base case B-01: Green hydrogen: MENA location, AEL electrolysis, renewable electricity mix, transport by ship (H_2 carrier NH_3, 4,000 km)**

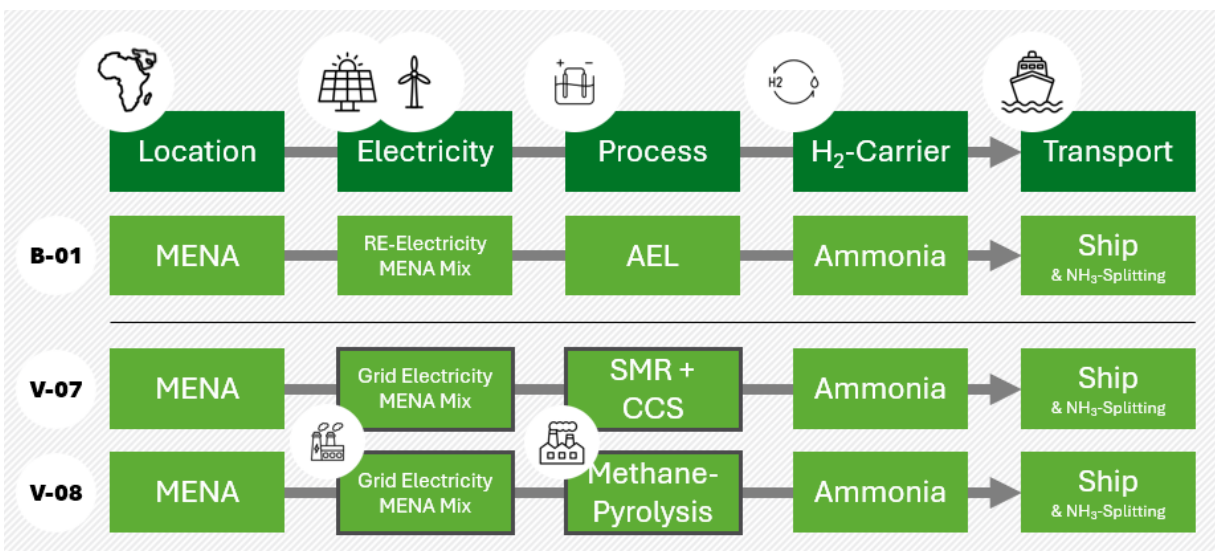
This base case is modified by varying different process parameters. The variations relate to individual processes such as hydrogen production, locations, hydrogen carriers or transport; they are presented below.

- **Variations: blue/turquoise hydrogen**

Keeping the production location (MENA) and transport mode to Germany (via NH_3 by ship) contant, the hydrogen colour is varied. In variation V-07, blue hydrogen is produced by steam reforming with CO_2 capture. Variation V-08 describes the production of turquoise hydrogen from methane pyrolysis with subsequent storage of the solid carbon. The varied processes along the supply paths are marked with a grey frame in Figure 12.

- V-07: Blue hydrogen: SMR with CCS, transport by ship (H_2 carrier NH_3)
- V-08: Turquoise hydrogen: pyrolysis of natural gas, C storage, transport by ship (H_2 carrier NH_3)

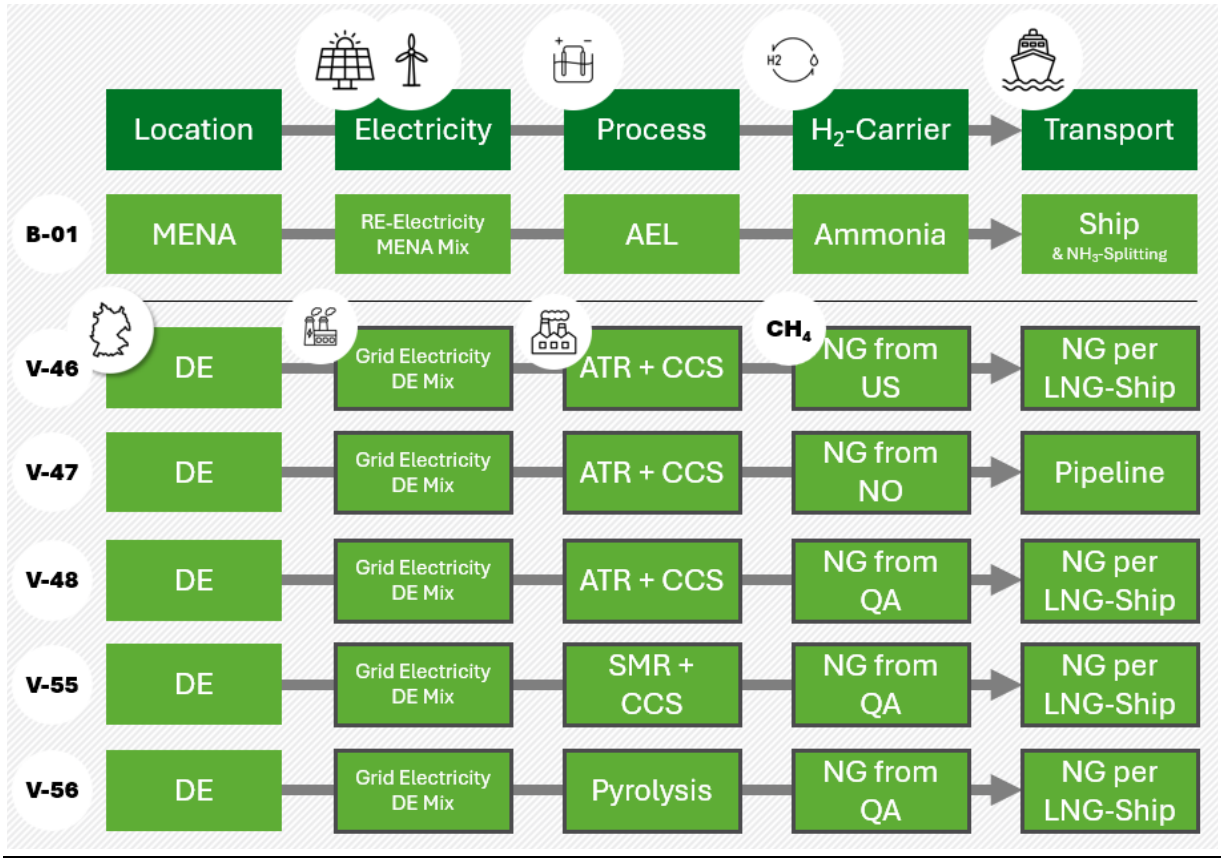
Figure 12: Hydrogen supply pathways by process in the base case (light green processes) and variations of blue/turquoise hydrogen. Processes that vary from the base case are outlined in grey.



MENA = Middle East/North Africa.
Source: Own representation, ifeu

In addition, five cases were added for the import of natural gas from various regions and hydrogen production in Germany (Figure 13). Variants V-46 to -48 show the variation in the production region with ATR and CCS as processes, while variants V-48, -55 and -56 show the variation in hydrogen production when importing natural gas from the MENA region, represented by Qatar. In all these variants, grid electricity is used to operate the plants in Germany.

Figure 13: Hydrogen supply paths by process in the base case (light green processes) and variations of blue/turquoise hydrogen with natural gas imports to Germany. Processes that vary from the base case are outlined in grey.



MENA = Middle East/North Africa.
Source: Own representation, ifeu

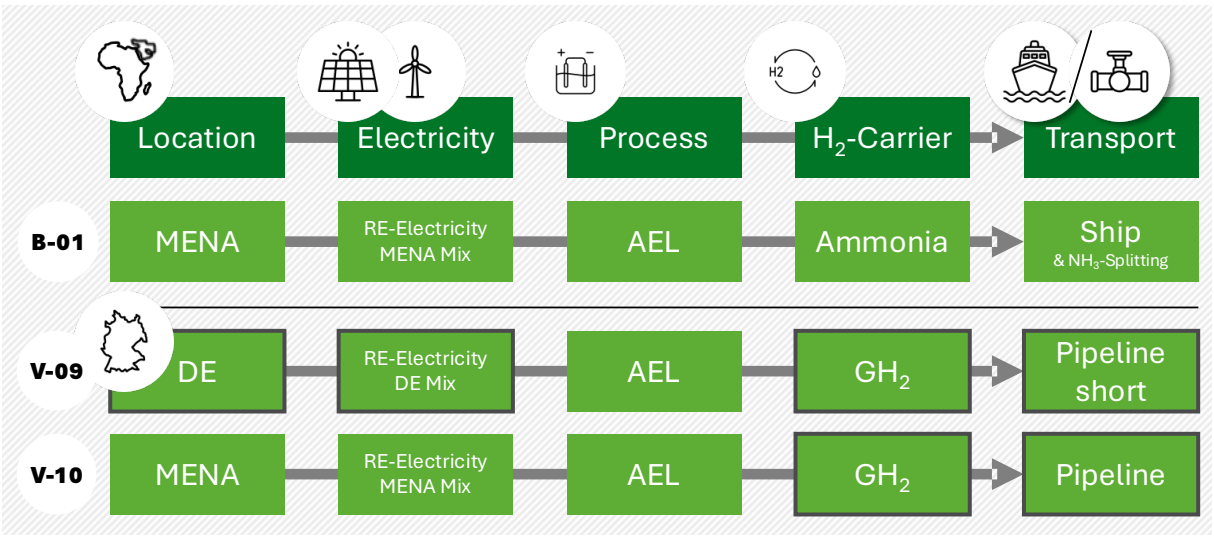
- **Variations: Location (MENA/DE), transport of green hydrogen via pipeline**

Keeping the production technology contant (AEL electrolysis), the production locations of green hydrogen and thus the corresponding renewable electricity mixes and transport routes are varied. In variation V-09, green hydrogen is produced in Germany (DE) and transported to its destination in gaseous form via a hydrogen pipeline; the assumed pipeline distance is 450 km within DE. Variation V-10 describes the production of green hydrogen in the MENA region, analogous to the base case, with subsequent pipeline transport over a distance of 3,000 km to DE. The varied processes along the supply paths are marked with a grey frame in Figure 14.

- V-09: Green hydrogen (GH_2) from Germany + pipeline (400 km high-pressure transmission network + 50 km low-pressure distribution)

- V-10: Green hydrogen (GH_2) from MENA + pipeline (3000 km high-pressure transmission network + 50 km low-pressure distribution)

Figure 14: Hydrogen supply paths according to processes in the base case (light green processes) and variations in location and transport (pipeline). Processes that vary from the base case: outlined in grey.



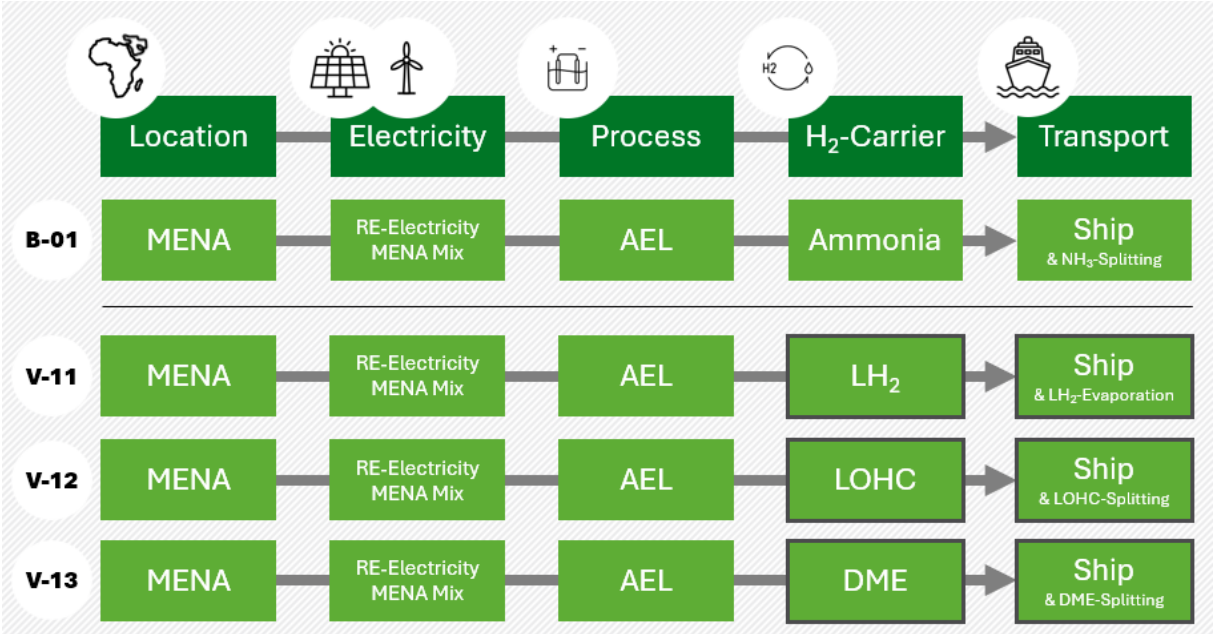
MENA = Middle East/North Africa, GH_2 = gaseous hydrogen.
Source: Own representation, ifeu

- **Variations: H_2 carriers (LH_2, LOHC, DME) + ship transport 4,000 km**

Keeping the production location (MENA) and the hydrogen production technology (AEL) constant, the hydrogen carrier is varied. In V-11, liquefied hydrogen (LH_2, liquid H_2), liquid organic H_2 carriers (LOHC, Liquid Organic Hydrogen Carrier) in V-12, and dimethyl ether (DME) in V-13 are assumed as possible hydrogen carriers. In DE, the hydrogen is vaporised or recovered from LOHC and DME by splitting. In the case of transport in the form of LOHC and DME, the carbon used to bind the hydrogen is returned to the production site (MENA) by sea in the form of "empty LOHC" or CO_2. The varied processes along the supply paths are marked with a grey frame in Figure 15.

- V-11: Green hydrogen from MENA + ship (LH_2) 4,000 km
- V-12: Green hydrogen from MENA + ship (H_2 carrier LOHC) 4,000 km with return transport of the "empty LOHC" (C cycle)
- V-13: Green hydrogen from MENA + ship (H_2 carrier DME) 4,000 km with return transport of C as CO_2 (C cycle)

Figure 15: Hydrogen supply paths by process in the base case (light green processes) and variations H_2 carrier (ship, 4,000 km). Processes that vary from the base case: outlined in grey.



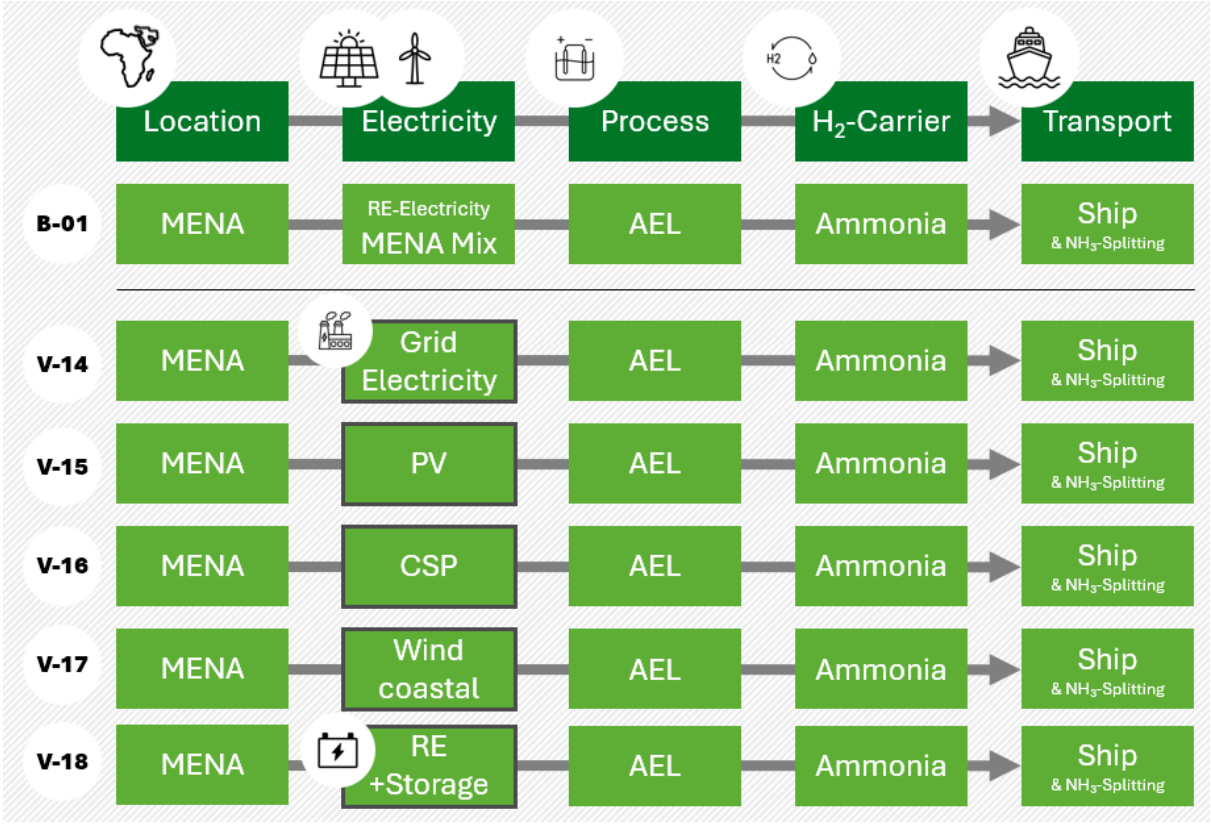
MENA = Middle East/North Africa, LH_2 = Liquid H_2, LOHC = Liquid Organic Hydrogen Carrier, DME = Dimethyl Ether.
Source: Own representation, ifeu

- **Variations: Electricity mix**

Keeping the production location (MENA) and the hydrogen production technology (AEL) constant, the electricity mix used in the MENA region is varied. The variations include both the use of grid electricity from the supply mix (in V-14) and various renewable options: in V-15, directly available electricity from photovoltaics (PV); in V-16, electricity from concentrated solar power (CSP); in V-17, electricity from wind energy at coastal locations; in V-18, renewable electricity stored in redox flow energy storage systems to increase the number of full-load hours. As in the base case, the hydrogen produced is transported by sea to Germany in the form of NH_3 and is converted there to H_2. The varied processes along the supply paths are marked with a grey frame in Figure 16.

- V-14: Supply mix of grid electricity at the site for all processes along the process chain
- V-15/V-16/V-17: 100% PV, CSP or wind turbine (wind, coastal location) as renewable extremes with limited full-load hours
- V-18: RE electricity mix of the location with redox flow electricity storage for 8,600 hours of electrolysis supply

Figure 16: Hydrogen supply paths according to processes in the base case (light green processes) and variations in electricity sources. Processes that vary from the base case: outlined in grey.



MENA = Middle East/North Africa, CSP = Concentrated Solar Power.
Source: Own representation, ifeu

- **Variations: autothermal reforming process with CCS; PEMEL electrolysis process and green ammonia synthesis**

In addition to the base case and the variations presented (production location, electricity mix, hydrogen production process, hydrogen carrier and transport routes), three additional variations are created. The varied processes along the supply paths are marked with a grey frame in Figure 17.

Variant V-19 corresponds to hydrogen production based on autothermal reforming of methane (ATR). The SMR (in variant V-07 for H_2) and ATR processes differ significantly in terms of CO_2 separation rates, among other things via CCS (see Table 7).

- V-19: Blue hydrogen: ATR + CCS

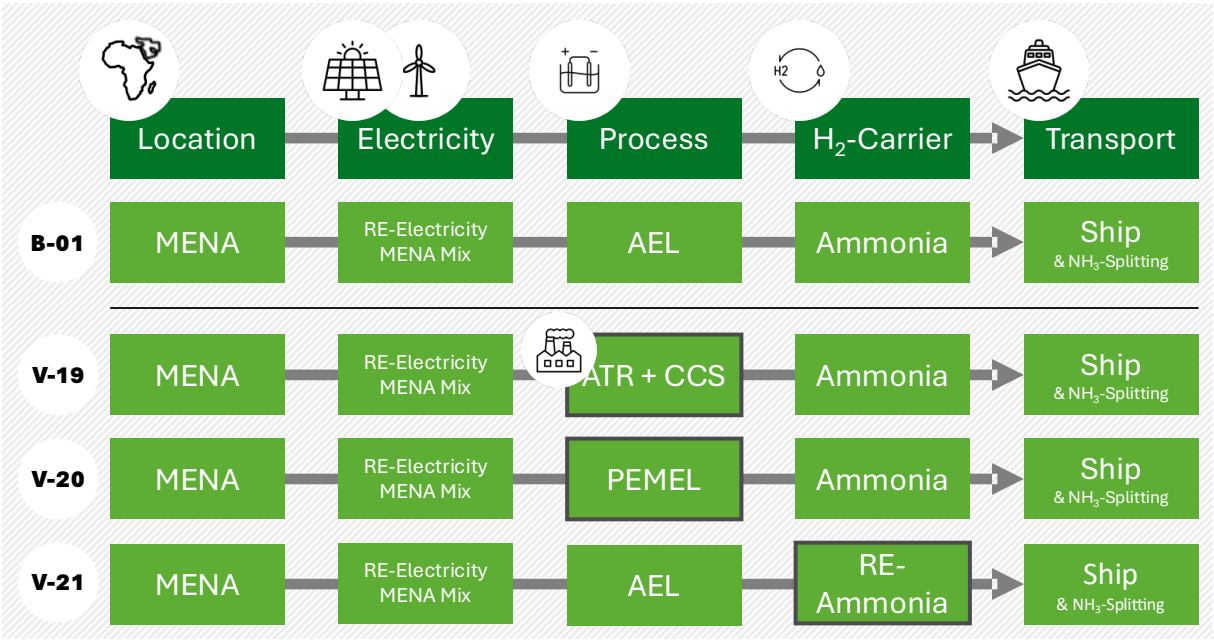
Variant V-20 refers to the variation in electrolysis technology. Here, green hydrogen is produced in the MENA region using polymer electrolyte membrane electrolysis (PEMEL) instead of alkaline electrolysis (AEL) as in the base case. The processes differ in terms of the materials used and resource requirements.

- V-20 Green hydrogen: PEMEL

Variant V-21 shows the influence of renewable electricity use on ammonia synthesis. Here, not only hydrogen but also ammonia is produced using renewable electricity. The green ammonia is split back into green hydrogen in Germany.

- V-21: Ammonia production using renewable electricity

Figure 17: Hydrogen supply paths according to processes in the base case (light green processes) and variations: production processes and H_2 carriers. Processes that vary from the base case: outlined in grey.



MENA = Middle East/North Africa, ATR = autothermal reforming, CCS = carbon capture and storage, PEMEL = polymer electrolyte membrane electrolysis.
Source: Own representation, ifeu

3.2 Ammonia

The variants considered in section 3.1 refer to the production and delivery of hydrogen to Germany (DE). This section deals with the production and delivery of ammonia to Germany, produced from hydrogen. The base case for ammonia production for use in Germany corresponds to the hydrogen base case: green hydrogen production in the Middle East and North Africa (MENA) region is assumed. The hydrogen is produced by alkaline electrolysis (AEL) using renewable (RE) electricity, converted into ammonia (NH_3) and transported by ship over a distance of 4,000 km. The green ammonia is then available for use in Germany. The top supply path shown and the light green processes in Figure 18 refer to the base case.

- **Base case B-02: Green ammonia: MENA location, AEL electrolysis, renewable electricity mix, Haber-Bosch synthesis, transport by ship (4,000 km)**

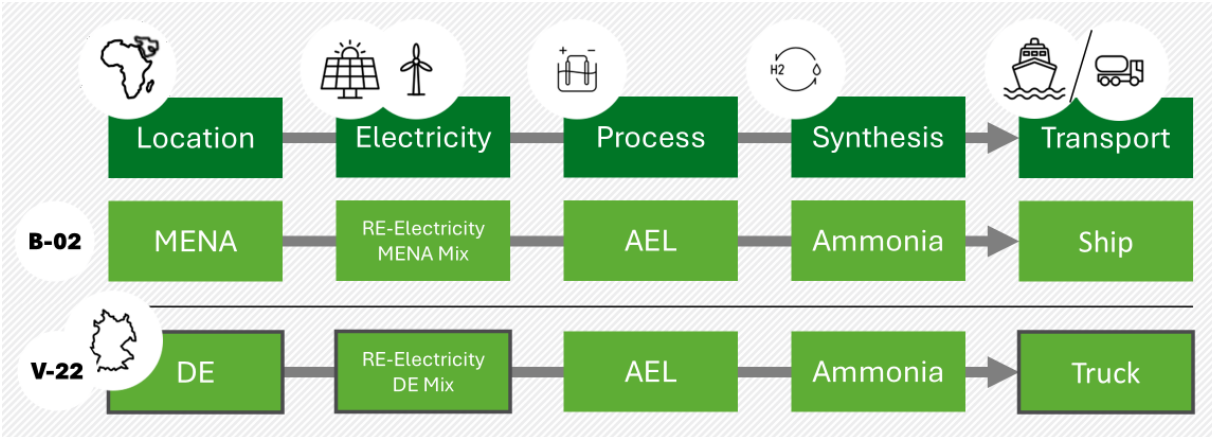
This base case is modified by varying the process parameters. The variant considered refers to the production location; it is presented below.

- **Variation: green ammonia from Germany**

Variation V-22 describes the production of green hydrogen in Germany by means of electrolysis (AEL) with the German renewable electricity mix followed by the production of ammonia. In Figure 18, the varied processes along the supply paths are marked with a grey frame.

- V-22: Green ammonia: Location DE (electrolysis + synthesis), Distribution by truck in DE over 400 km

Figure 18: Ammonia supply paths according to processes in the base case (light green processes) and variations in ammonia colour and location. Processes that vary from the base case: outlined in grey.



Abbreviations: MENA = Middle East/North Africa.
Source: Own representation, ifeu

3.3 Methane (SNG)

Synthetic methane is produced through the reaction of hydrogen and carbon dioxide (CO_2). The production of hydrogen as the first step corresponds to the base case B-01. The hydrogen is converted into synthetic methane at the production site using CO_2 (DAC, Direct Air Capture) to produce synthetic methane, which is liquefied and transported by ship (LNG) over a distance of 4,000 km to Germany. The top supply path shown and the light green processes in Figure 19 refer to the base case.

- **Base case B-03: MENA location, AEL electrolysis, renewable electricity mix, CO_2 from DAC, methane synthesis, transport by ship (LNG, 4,000 km)**

This base case is modified by varying the production location and transport of the synthetic methane to Germany; the variations are shown below.

- **Variations in location/transport and CO_2 source**

In variation V-23, green hydrogen is produced in Germany. The synthetic methane produced from it is distributed within Germany by pipeline (450 km).

Variation V-24 additionally modifies the CO_2 source, using captured CO_2 from biomethane plants.

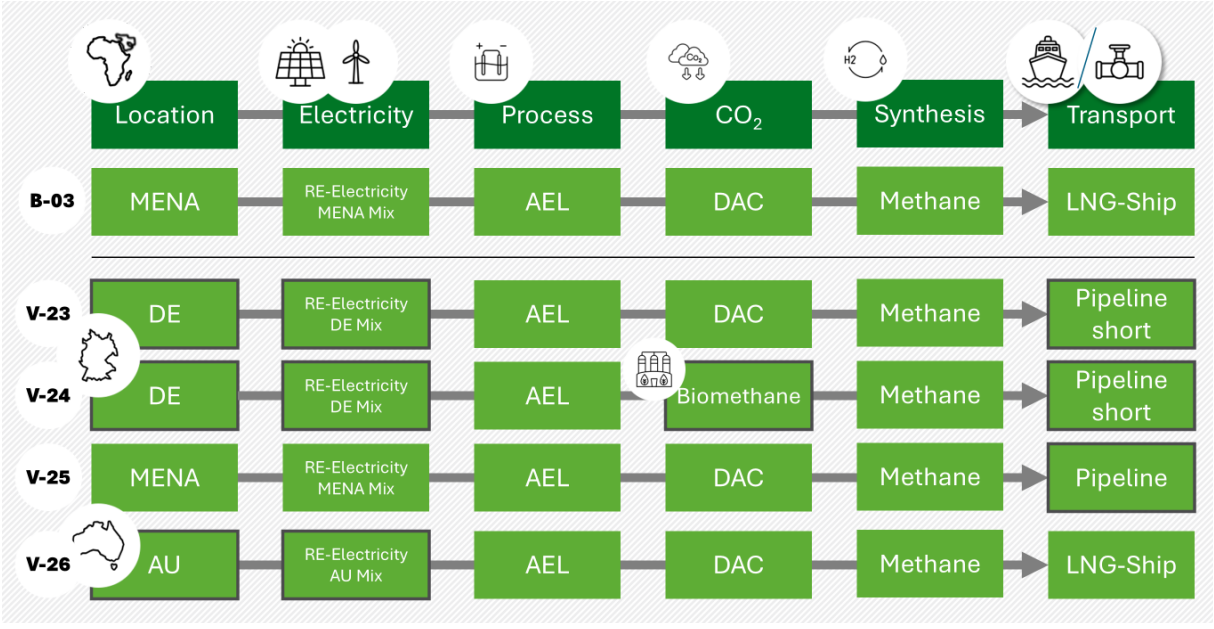
Variation V-25 describes the production of synthetic methane according to the base case with modified transport to DE; while the base case involves the transport of liquefied methane (LNG, liquefied natural gas) by ship over a distance of 4,000 km, this variation assumes transport via pipeline (3,000 km).

Variant V-26 also describes the transport of synthetic methane from green hydrogen by sea, but in this variant the production location is Australia, which increases the transport distance to 19,000 km.

In Figure 19, the varied processes along the supply paths are marked with a grey frame.

- V-23: DE + pipeline (400 km high-pressure transmission network + 50 km low-pressure distribution)
- V-24: DE + pipeline (see above), CO_2 from biomethane
- V-25: MENA + pipeline 3,000 km
- V-26: Australia + ship (LNG) 19,000 km

Figure 19: Supply paths for synthetic methane according to processes in the base case (light green processes) and variations in location/transport. Processes that vary from the base case: outlined in grey.



Abbreviations: MENA = Middle East/North Africa, AU = Australia, LNG = liquefied natural gas.
Source: Own representation, ifeu

3.4 Methanol

The production of synthetic methanol is also based on the conversion of hydrogen with carbon dioxide (CO_2). The base case for methanol production is chosen analogously to methane synthesis. The hydrogen is converted into synthetic methanol at the production site using CO_2 captured from the ambient air (DAC, Direct Air Capture), which is then transported by ship over a distance of 4,000 km to DE. The top supply path shown and the light green processes in Figure 20 refer to the base case.

- **Base case: MENA location, AEL electrolysis, RE electricity mix, CO_2 from DAC, methanol synthesis, transport by ship (4,000 km)**

This base case is modified by varying the production location and transport of synthetic methanol to Germany; the variations are shown below.

► **Variations: Location/transport**

In variant V-27, green hydrogen is produced in Germany. The synthetic methanol produced from it is distributed within Germany by truck (150 km).

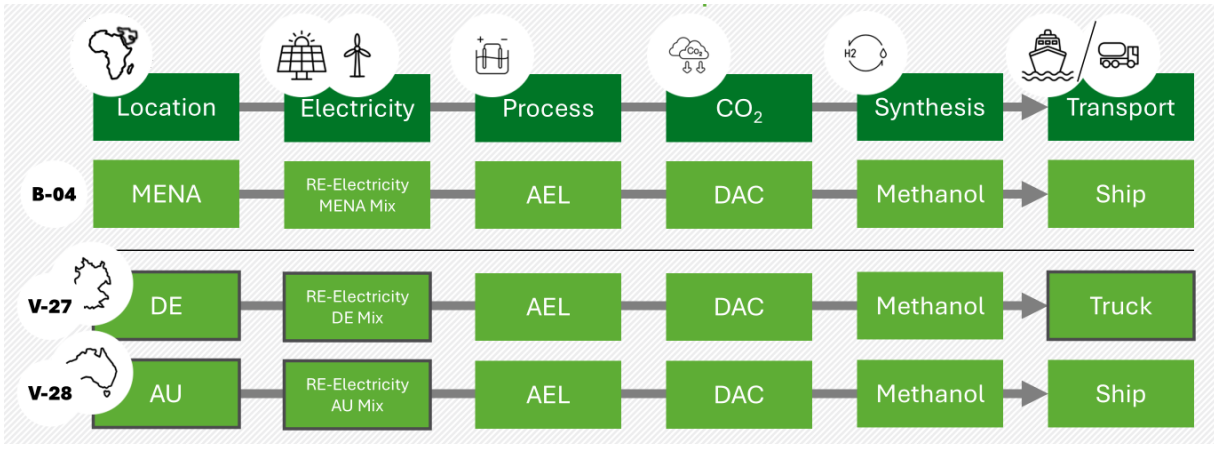
Variant V-28 describes the transport of synthetic methanol from green hydrogen from Australia by sea over a transport distance of 19,000 km.

In Figure 20, the varied processes along the supply paths are marked with a grey frame.

► V-27: DE (electrolysis + synthesis), truck 150 km

► V-28: Australia (electrolysis + synthesis), ship 19,000 km

Figure 20: Supply paths for synthetic methanol according to processes in the base case (light green processes) and variations in location/transport. Processes that vary from the base case: outlined in grey.



MENA = Middle East/North Africa, AU = Australia. Source: Own representation, ifeu

3.5 Dimethyl ether

DME is produced by dehydrating methanol. The base case and variations of dimethyl ether (DME) production correspond to the production of methanol, which is described in section 3.4. In hydrogen variant V-13, the production and supply of DME to Germany is already considered, with DME being used as a hydrogen carrier. In contrast to the DME variant of the hydrogen pathways, in this case the required CO_2 is obtained from the ambient air (DAC, Direct Air Capture) and is not returned after the splitting of DME from Germany (compare Figure 15). The top supply pathway shown and the light green processes in Figure 21 refer to the base case; the varied processes along the supply pathways are indicated by a grey frame.

► **Base case B-05: MENA location, AEL electrolysis, RE electricity mix, CO_2 from DAC, methanol/DME synthesis, transport by ship**

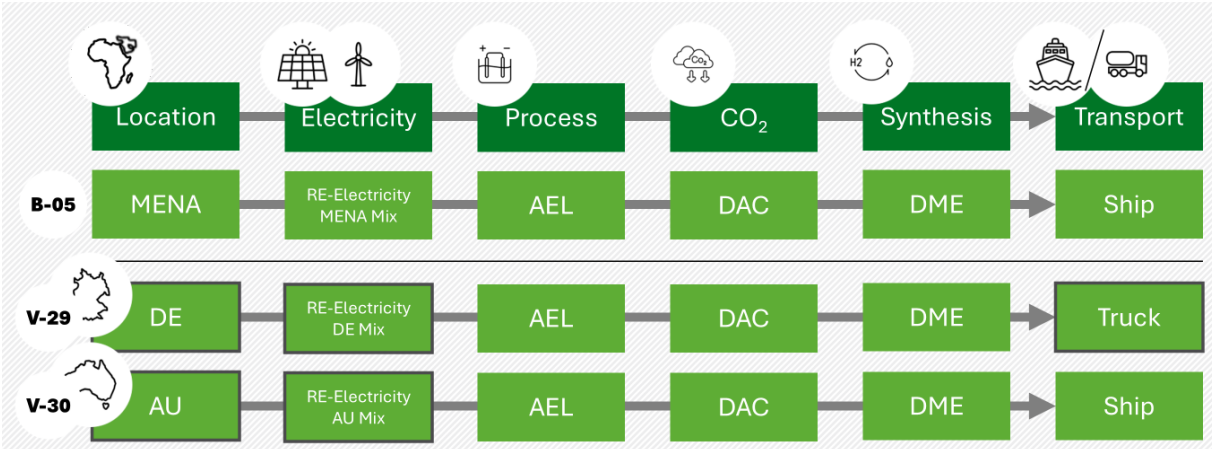
This base case is modified by varying the production location and transport of dimethyl ether to Germany; the variations are shown below

► **Variations: Location/transport**

In variant V-29, hydrogen is produced in Germany and transported only a short distance by truck, while in variant V-30, DME is produced in Australia and transported to Germany by ship.

- V-29: DE (electrolysis + synthesis), truck 150 km
- V-30: Australia (electrolysis + synthesis), ship 19,000 km

Figure 21: Supply paths for DME according to processes in the base case (light green processes) and variations in location/transport. Processes that vary from the base case are outlined in grey.



MENA = Middle East/North Africa, AU = Australia. Source: Own representation, ifeu

3.6 Petrol/diesel/kerosene/naphtha

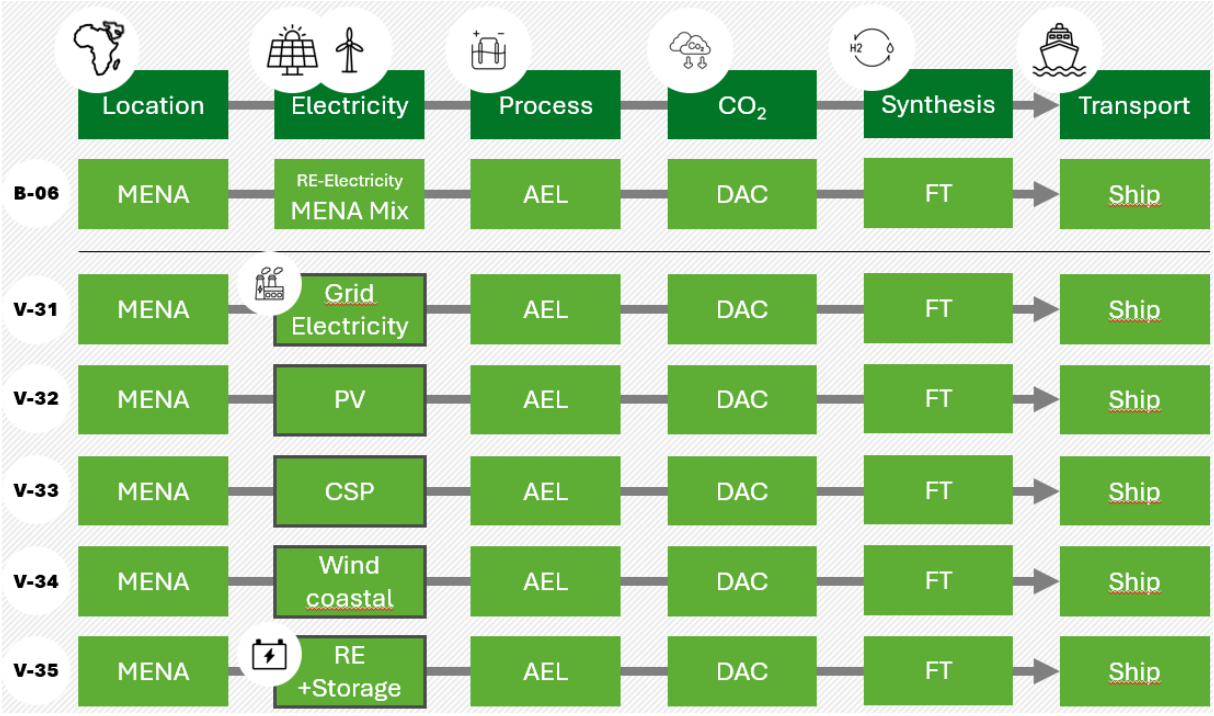
The base case for the production of the synthetic fuels mentioned (petrol, diesel, kerosene, naphtha) starts with the base case for the production of green hydrogen B-01. Hydrogen and CO_2 from the ambient air (via DAC, direct air capture) are used to produce synthesis gas, which is then used to produce power-to-liquid (PtL) fuel via Fischer-Tropsch synthesis (FT). The top supply path shown and the light green processes in Figure 22 refer to the base case.

- **Base case B-06: MENA location, AEL electrolysis, RE electricity mix, CO_2 from DAC, FT synthesis, transport by ship (4,000 km)**

The varied processes along the supply paths correspond to the variations in hydrogen production in Figure 16 and include, in variant V-31, the use of grid electricity from the supply mix ("grey" hydrogen) and, in variants V-32/V-33/V-34, different renewable electricity supplies from one generation type each, and in variant V-35, the use of the renewable electricity mix and redox flow electricity storage systems to increase the number of full-load hours. The variations are marked with a grey frame in Figure 22.

- **Variations: Electricity mix**
- V-31: Grid electricity supply mix for all processes along the process chain
- V-32/V-33/V-34: 100% PV, CSP or 100% wind energy (coastal location) as renewable extremes with limited full-load hours
- V-35: RE electricity mix with redox flow electricity storage for 8,600 hours of electrolysis supply

Figure 22: Supply paths for synthetic fuels according to processes in the base case (light green processes) and variations in electricity sources. Processes that vary from the base case: outlined in grey.



MENA = Middle East/North Africa, CSP = Concentrated Solar Power, FT = Fischer-Tropsch.

Source: Own representation, ifeu

- **Variations: CO_2 source and synthesis technology for petrol**

In two variations, the base case B-06 is modified with different CO_2 sources. Unlike in the case of extraction from the ambient air (DAC, Direct Air Capture) in the base case, point sources are used in the variations.

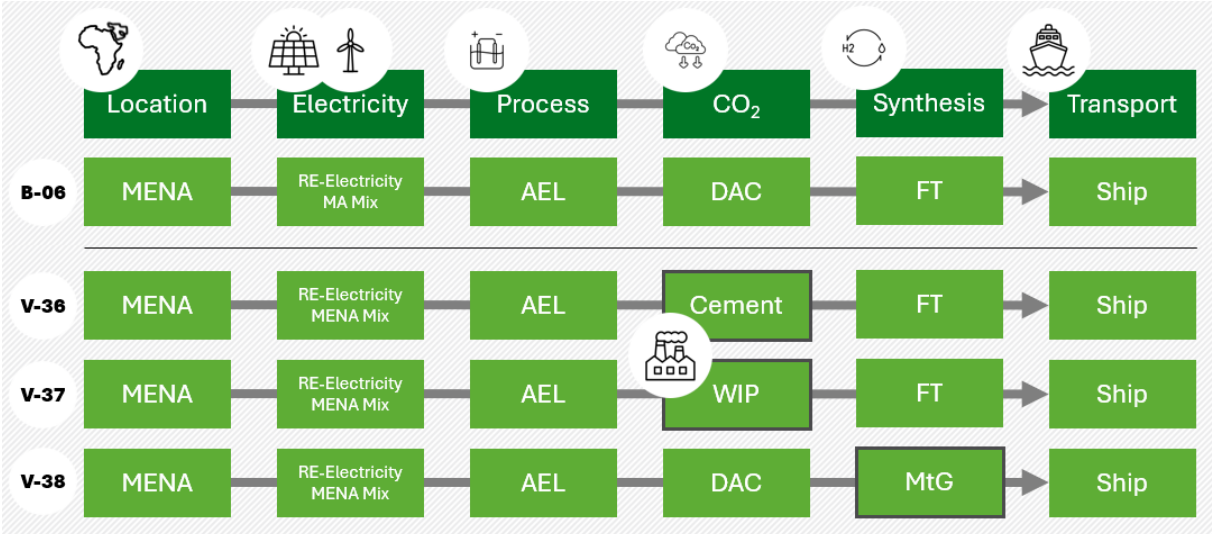
In variation V-36, process-related (mineral) CO_2 emissions from lime burning in cement plants are used. The production location remains the MENA region. Variation V-37 uses CO_2 from waste incineration (WIP) in the MENA region. In Figure 23, the varied processes along the supply paths are marked with a grey frame.

- V-36: cement plant
- V-37: Waste incineration plant (WIP)

In addition to the processes for producing hydrogen and recovering CO_2, variant V-38 varies the fuel synthesis process. Instead of Fischer-Tropsch synthesis, the methanol-to-gasoline (MtG) process is used to produce petrol. The fuel is produced in the MENA region and transported to Germany by sea, as in the base case.

- V-38: Methanol-to-gasoline (MtG)

Figure 23: Supply paths for synthetic fuels according to processes in the base case (light green processes) and variations in CO_2 sources. Processes that vary from the base case: outlined in grey.



MENA = Middle East/North Africa, WIP = waste incineration plant, FT = Fischer-Tropsch, MtG = methanol-to-gasoline.
Source: Own representation, ifeu

4 Climate and environmental effects of the manufacture of PtGLS products

4.1 Methodological basis of the life cycle assessment

The life cycle assessment includes modelling the selected process chains with the corresponding supply processes and transport to Germany for the hydrogen carriers under consideration. In addition to selecting the system boundaries, which include all relevant processes, the modelling also involves choosing a functional unit and a software solution in which all material flows can be recorded and evaluated (see section 4.1.1). The model is based on a model structure that is filled with process parameters and assumptions. The central process parameters were presented in the description of the provision processes in the previous sections. The information comes from publications and specialised databases (see section 4.1.2). An important basis for the life cycle assessment is the methodological decision regarding the allocation of environmental impacts in processes with multiple products; the allocation methodology is presented in section 4.1.3. The result of the life cycle assessment is the evaluation of the modelling in the form of a series of selected environmental impact categories (see section 4.1.4).

It is important to note that the results of the following calculations may differ from those of other publications. This is due to a different database, different assumptions and modelling principles. In particular, the results according to the calculation rules of Delegated Regulation (EU) 2023/1185 to Directive (EU) 2018/2001 ("Renewable Energy Directive" or "RED") lead to different results. For example, these calculation rules do not include the burdens from the manufacture and disposal of the infrastructure. As a result, electricity from photovoltaics or wind has zero emission factors.

4.1.1 Model description

This study considers all processes along the production chain. As shown in Figure 24, the following process steps are included in the **system boundaries**:

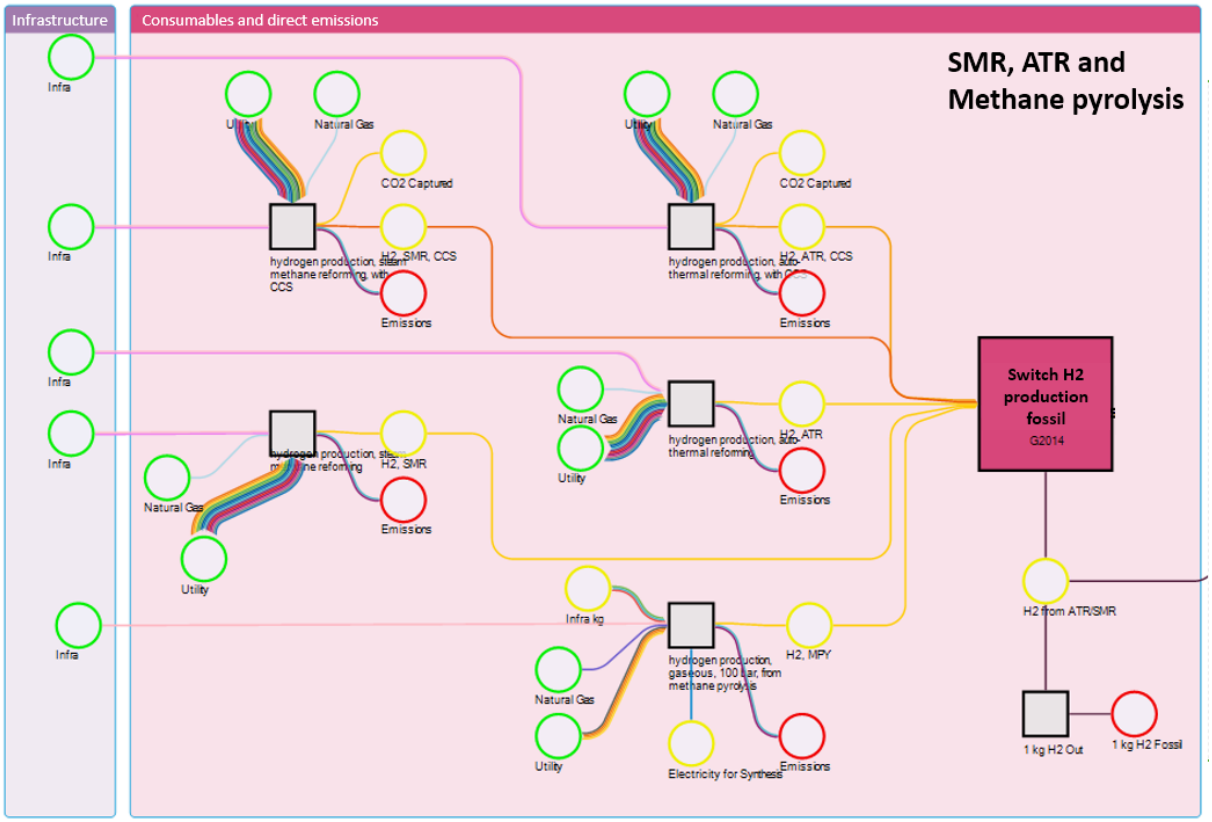
- Extraction and transport of fossil fuels for electricity and/or heat generation
- Provision of electrical energy
- Provision of thermal energy
- Provision of biomethane (variation in CO_2 source)
- Operation of plants for water electrolysis, CO_2 capture, product synthesis and processing, return transport of the "unloaded" LOHC
- Infrastructure and operating materials for plants and means of transport, in particular for the provision of renewable energy, electrolysers and synthesis plants
- Upstream chains for all materials used in the above-mentioned processes
- Emissions from the end of life (EoL) of production plants

Emissions and waste generated at the end of the product's life are not included in the system boundaries specified here.

The **functional unit** in the models is set at 1 MJ (LHV, lower heating value) of the energy carrier so that the results are comparable with each other. The products are supplied in Germany.

The mass and energy flows for the foreground processes (see Figure 24) are modelled using the material flow and life cycle assessment software "Umberto 11". Data for background processes was taken from the life cycle assessment database ecoinvent v3.11 (ecoinvent 2024; Wernet et al. 2016). In parallel, the model was implemented in the open source framework for life cycle assessment (LCA) "Brightway". This allows for a more in-depth analysis of the underlying environmental impacts.

Figure 24: Umberto 11 sub-model screenshot – SMR, ATR and methane pyrolysis.



Source: Own representation, screenshot, ifeu.

4.1.2 Data basis

Key process parameters for the provision processes of the PtGLS products examined and the associated literature sources are presented in section 2. A more detailed compilation of all parameters used in the modelling can be found in the separate technical appendix.

Information from the ecoinvent v3.11 life cycle assessment database (ecoinvent 2024; Wernet et al. 2016) is used for background processes such as upstream energy sources (extraction and processing), the supply of electricity, and the provision of chemicals and other raw materials.

4.1.3 Allocation

The handling of by-products requires a number of methodological decisions to be made with regard to the allocation of raw material requirements and environmental impacts. Raw materials and materials used, as well as emissions and waste, are allocated to the products of a process. The key condition for successful allocation is the conservation of mass and energy flows, whereby different methodological approaches to allocation can be chosen. The requirements and impacts of a process can be distributed and allocated based on the mass ratios of the products, their economic value, energy content or other benefits, for example.

The following approaches apply to the allocation rules defined in this study:

- For processes with more than one value product, physical allocations based on energy (lower heating value, LHV) or exergy content are applied where possible. Thermal energy and electrical energy are also considered value products and are allocated according to their exergy content.
- The use of a by-product within the supply path ("closed loop") is credited in the balance sheet. The same applies to thermal and electrical energy from synthesis processes: in the balance sheet, this replaces the corresponding energy in upstream processes such as electrolysis or CO_2 capture. Beyond this, no credits or debits are assigned.
- The following specifications have been made with regard to CO_2 provision for synthesis products: CO_2 emitted from a process that aims to produce a valuable product (such as cement production or power generation in a power plant) is considered "waste for recycling". All burdens of the upstream chain (raw material provision, transport, pre-processes) and the main process itself are allocated to the respective value-added product. In particular, the burdens for carbon from fossil sources are not allocated to the PtX product. However, these carbon quantities are listed for information purposes.

4.1.4 Impact categories and assessment systems

The mathematical modelling is evaluated according to the following impact categories and assessment systems as compiled in UBA 2016 (Detzel et al. 2016):

- Climate change: Global Warming Potential (GWP 100a) according to (IPCC 2021) in g CO_2-eq.
- Resource use: Cumulative energy demand (CED) in MJ (HHV)
- Resource use: Abiotic Depletion Potential, Elements (ADP) in kg Sb-eq. (CML 2016)
- Acidification: Acidification Potential (AP) according to (Hauschild and Wenzel 1998) in g SO_2-eq.
- Summer smog: Photochemical Ozone Creation Potential (POCP) according to ReCiPe (Goedkoop et al. 2009) in g C_2H_4-eq.
- Eutrophication: Eutrophication Potential (EP) according to (Heijungs et al. 1992) in g PO_4-eq.
- Ozone depletion: Ozone Depletion Potential (ODP) according to (WMO 2014) in g CFC-11-eq.
- Particulate matter: Particulate matter <2.5 µm (PM2.5) according to (De Leeuw 2002; WHO 2006) in g PM2.5 eq.
- Land use: Hemerobic weighted land use according to (Fehrenbach et al. 2015, 2019) in m^2aLe · a (aLe = artificial land equivalents)
- Water demand: Demand for fresh water for processes (no cooling water) in l H_2O, without further evaluation by scarcity indicators. For further details on water use and availability, see chapter 4.2.

In the impact categories, individual emissions (or requirements) that potentially cause the corresponding environmental impact to a known extent are combined into a uniform indicator using characterisation factors. An emission can contribute to one or more different environmental impact categories: for example, nitrogen oxides contribute simultaneously and

with different characterisation factors to the indicators acidification, eutrophication, particulate matter pollution and others, while carbon dioxide is only attributed a climate impact.

In addition to the climate-relevant substances specified by the IPCC, emissions of hydrogen along the process paths (e.g. through evaporation losses) are also proven to have a climate impact. According to a recent publication by (Chen et al. 2024), the GWP_{100} of hydrogen is between 6 and 17 and is set at a value of 10 for this study.

4.2 Use and availability of water

4.2.1 Types of water use

Water is used at various points in the process chains. A distinction must be made between:

- **Process water**, which is used as a reactant in the process itself, e.g. in electrolysis or steam reforming of methane. High purity requirements often have to be met here, as impurities can deposit in the reactor, damage the catalyst or lead to undesirable by-products.
- **Boiler feed water**, which is used to generate steam, which in turn is used to heat reactors and apparatus or to drive a steam turbine. For this application, salts of alkaline earth metals and dissolved gases in particular must be removed, as they form insulating layers on surfaces when heated or have a corrosive effect. Most of the boiler feed water is circulated in a closed circuit. A small partial flow is removed to regulate the concentration of salts in the circuit (desalination). This flow, as well as any losses in the process, must be replaced with fresh water.
- **Cooling water** is used to remove heat from the process. The quantity and required purity depend on the cooling method used:
  - Continuous cooling, for example with river water or sea water, requires a large amount of water at the inlet, but practically all of the water is discharged from the process again, apart from an evaporation loss of approx. 1%. The water quality requirements are low. However, biocides are often added to fresh water to prevent fouling (algae/bacterial growth) in the cooling system. These biocides enter the environment with the outgoing cooling water unless the cooling water is treated (typical order of magnitude 0.1-0.5 g free oxidants/m^3 (European Commission 2001)).
  - A cooling water recirculation system with evaporative cooling has a lower water requirement at the inlet. Since a large proportion (> 90%) of the water evaporates during cooling, the water consumption is significantly higher than the consumption of continuous flow cooling. At the same time, desalination (especially decalcification) of the cooling water is necessary to prevent deposits in the cooling system.

4.2.2 Water availability

The following options are generally available as water sources:

- Surface water, e.g. from rivers or lakes
- Groundwater
- Sea or brackish water
- Industrial or municipal wastewater

Climate change is altering the availability of water, particularly groundwater and surface water, both in Germany and globally. This is also giving rise to conflicts of use between drinking water supply, irrigation of agricultural land and industrial use. A detailed description of the availability of water today and in the future is not possible at this point[6]. However, factors describing the respective local water availability should be taken into account when selecting the water source.

At this point, it is recommended not to use fresh water from groundwater or surface water as process water for the production of hydrogen or derivatives if one of the **following limit values** is exceeded:

- **Quotient of the safe operating space of a watershed and total human water consumption** in the catchment area of the location in question according to Bunsen et al. (2022)[7] is **greater than 1** on an annual average (or even in individual months), indicating that the local carrying capacity limits of the catchment area are being exceeded.
  - The safe operating space of a watershed is derived from the natural water supply (= sum of surface runoff and groundwater recharge, determined from the global hydrological model WaterGAP3 (Alcamo et al. 2003; Döll et al. 2003)), from which the environmentally-related water flow requirements (= the proportion of natural water resources required to maintain local aquatic ecosystems in an appropriate ecological condition (Pastor et al. 2014)) are subtracted.
  - Total human water consumption is also taken from WaterGAP3 (aus der Beek et al. 2010; Flörke et al. 2013). It includes domestic water consumption (households and small businesses), industry, cooling water, irrigation in agriculture and livestock farming.
- An **AWARE[8] factor** (Seitfudem et al. 2025) **greater than 20** in individual months or as an annual average. The AWARE factor indicates, in comparison to the global average, how much water per area remains after the needs of humans and aquatic ecosystems have been met. A value of 1 corresponds to the global average and a value of 10 to a region that has on average 10 times less water available than the global average. The upper limit is set at 100 for regions where withdrawal exceeds the amount of water available.
- A **water use index** (e.g. Aqueduct 4.0 Baseline Water Stress (Kuzma et al. 2023)[9] or Water Exploitation Index plus, WEI+) **greater than 20%.** This measures water consumption as a percentage of renewable freshwater resources at the level of river basins or sub-units. Values above 20% indicate that water resources are under stress and therefore water scarcity exists, while values above 40% mean that water stress is severe and the level of freshwater use may be unsustainable (Raskin et al. 1997).
  - The Aqueduct indicator is based on the PCR-GLOBWB 2 hydrological model. On the withdrawal side, it takes into account the household, industrial, irrigation and livestock sectors, including both gross and net withdrawals (i.e. minus returns to the original system). Water availability is determined from the amount of inflowing water (surface

[6] The development of water availability in Germany was examined in detail in the UBA project WADKlim (Flörke et al. 2024)

[7] Regionally resolved data for this quotient are available at https://wf-tools.see.tu-berlin.de/wf-tools/der-wasserfussabdruck-von-deutschland-zusatzmaterialien/Charakterisierungsfaktoren/

[8] AWARE = Available Water Remaining; regionally resolved data is available at https://zenodo.org/records/15133241

[9] Regionally resolved data for the Aqueduct Baseline Water Stress is available at https://www.wri.org/data/aqueduct-global-maps-40-data

water and groundwater minus consumption in the upper reaches), minus outflows to a sub-region. The calculation is performed monthly or as an annual average.

- The Water Exploitation Index is calculated in a similar way but refers to the average water availability for a specific period, e.g. 1991-2020. Renewable freshwater resources are calculated from the difference between precipitation and evaporation from soil and plants, plus inflows from other regions. The data basis for Europe is provided by "Waterbase — Water Quantity database" (European Environment Agency 2024), the Eurostat database (Eurostat 2024a; b) and the LISFLOOD Model of the Joint Research Centre (Institute for the Protection and Security of the Citizen (Joint Research Centre) et al. 2013)

The availability of water is highly dependent on the actual location and the water catchment area and is subject to seasonal fluctuations. For an accurate assessment of a location, the analysis should be carried out on a regional basis or on the basis of water catchment areas, taking into account monthly or quarterly averages.

Table 22 provides examples of some of the factors described as national annual values for Germany, Morocco, Spain, Chile, Canada, Australia and South Africa. It is obvious that locations in Spain, Morocco and Chile exceed the limit values in all indicators and therefore no fresh water should be used there. In Australia and South Africa, the situation is unclear; the resilience limit does not appear to have been exceeded there. However, a more detailed analysis of the parameters cannot be carried out in this study.

The evaluation of water demand in this study is based purely on inventory, i.e. without the application of a scarcity indicator, as the selected locations are only examples. Depending on the location, water for the processes can be supplied from various sources, including, in some cases, desalination of seawater with the associated increased energy consumption (see section 2.15).

Table 22: Selected indicators of water scarcity for selected countries (exceedances of the proposed thresholds are shown in bold); annual averages for entire countries; subnational and monthly values may vary.

	Relative exceedance of the safe operating space[a]	Relative remaining water volume[b]	Water use index[c]
Country			
Germany	0.11	2.3	20-40% (2.04)
Morocco	**8.0**	**91.9**	**40-80% (3.99)**
Spain	**8.0**	**73.5**	**40-80% (3.94)**
Chile	**2.9**	**88.1**	**>80% (4.47)**
Canada	0.02	7	10-20% (1.23)
Australia	0.5	**79.4**	**20-40% (2.91)**
South Africa	0.35	**66.1**	**>80% (4.17)**
Proposed limit for the indicator for fresh water use	**1.0**	**20**	**20% (2.0)**

Source: a) (Bunsen et al. 2022), b) AWARE 2.0 (Seitfudem et al. 2025), c) Aqueduct 4.0 (Kuzma et al. 2023).

4.3 Results

The following figures show the environmental impacts of the PtGLS products examined, each based on 1 MJ of heating value (LHV). Using heating value as the basis allows for comparability within different supply paths for a product as well as between different PtGLS products. The specific heating values and reference emissions shown in Table 23 apply.

Table 23: Calorific values (LHV) of the PtGLS products examined and GHG emissions of the fossil reference products.

Product	Calorific value	CF Fossil reference
Hydrogen	120 MJ/kg	95 g CO_2-eq./MJ
Ammonia*	18.8 MJ/kg	151 g CO_2-eq./MJ
Methane (SNG)	47.5 MJ/kg	69 g CO_2-eq./MJ
Methanol	19.9 MJ/kg	114 g CO_2-eq./MJ
Dimethyl ether**	28.4 MJ/kg	119 g CO_2-eq./MJ
Petrol/diesel/kerosene ("FT")	44,.0 MJ/kg	99 g CO_2-eq./MJ
MtG fuel	43.0 MJ/kg	97 g CO_2-eq./MJ

* Deviation from original source: higher calorific value due to small proportion of H_2 in the product.

** Deviation from original source: lower calorific value due to small proportion of CO_2 in the product. CF = carbon footprint including combustion Source: National Institute of Standards and Technology (NIST) (Linstrom 2021), ecoinvent 3.11 (ecoinvent 2024; Wernet et al. 2016).

The results of the calculations are presented in stacked bar charts. The Y-axis shows the impact in the respective environmental impact category (e.g. greenhouse gas potential in g CO_2 eq./MJ H_2 carrier), while the X-axis shows the individual variants side by side in comparison. The columns provide a contribution analysis and are divided according to the production steps and life cycles of the PtGLS products:

Table 24: Life cycle stages broken down in the life cycle assessment results.

Process step	Activities considered	Colour
Infrastructure	Construction and disposal of electrolysers, CO_2 capture plants and synthesis plants – excluding consumables.	
Electricity for Electrolysis	Electricity requirements for the electrolytic production of hydrogen	
Energy CO_2 capture	Energy requirements for CO_2 capture	
CCS	Energy and direct emissions for transport and sequestration of CO_2	
Electricity for Synthesis	Electricity requirements synthesis of hydrogen for the respective derivative	
Consumables and direct emissions	Catalysts, electrolytes, water supply and direct emissions for electrolysers, CO_2 capture and synthesis plants. Adsorbent and absorbent materials for CO_2 capture.	
Supply of natural gas/LNG	Fossil natural gas supply, emissions and infrastructure, compression to LNG if necessary, transport	

Process step	Activities considered	Colour
Transport medium	Synthesis and reconversion of H_2 transport media (NH_3, LOHC, DME)	
Transport	Transport of products and transport media as well as construction and disposal of ships, lorries and pipelines	

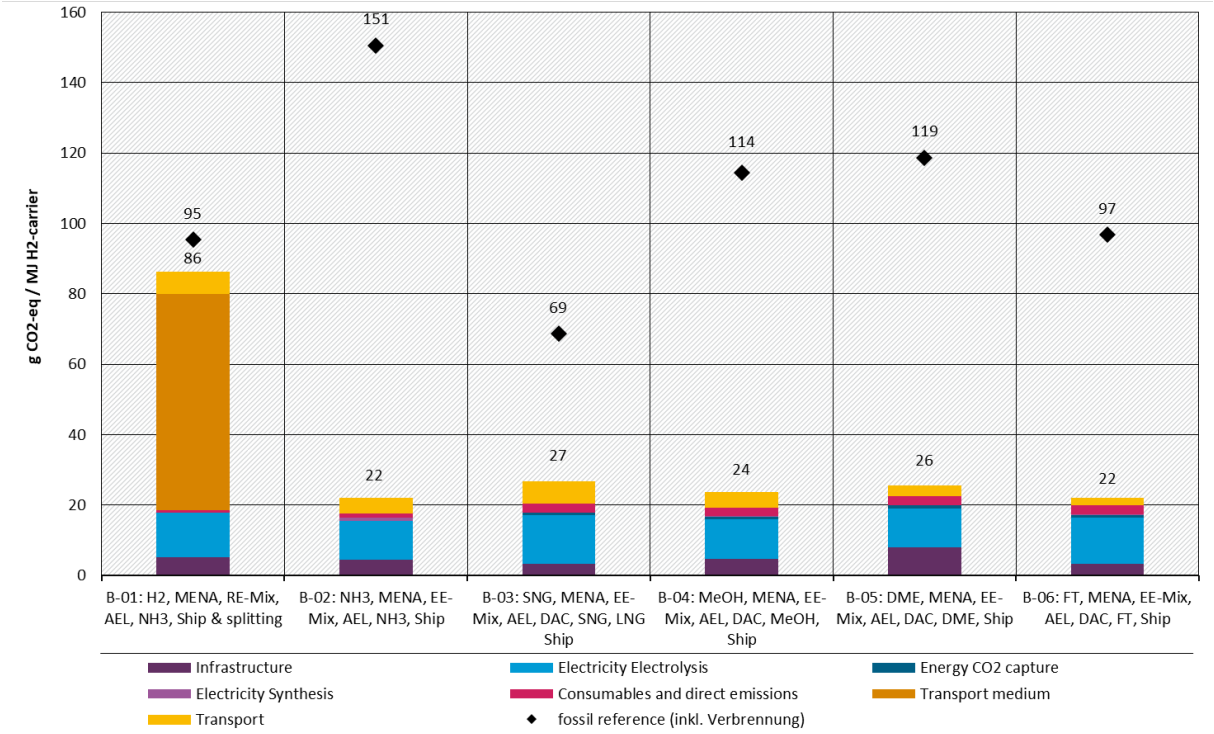
Reference values for conventional fossil fuels in Europe are shown as black diamonds in the diagrams with the base variants. In the impact category climate change, including combustion, and in all other categories, excluding combustion/use.

4.3.1 Climate change

4.3.1.1 Base cases

The following Figure 25 shows the results for the carbon footprint of the PtGLS products considered in the respective base case, based on 1 MJ of calorific value. The stacked columns show the contributions of the process stages according to Table 24.

Figure 25: Carbon footprint of the provision of PtGLS products in the base case



Source: own representation, ifeu.

Among the base cases shown, the production of hydrogen (H_2) in the MENA region with subsequent transport to Germany via ammonia (NH_3) (base case B-01) has by far the highest carbon footprint. Compared to the fossil reference, the carbon footprint is around 10% lower. The results for the other products are significantly lower. Compared to the fossil references, synthetic natural gas (B-03) achieves a reduction of around 60%, while all other products achieve reductions of around 80-85%.

The largest contribution to base case B-01 comes from the "transport medium" process step – primarily through the production of ammonia using the Haber-Bosch process. Grey electricity from the supply mix in the MENA region is used here. The splitting of the transport medium NH_3 into H_2 in Germany is also carried out using grid electricity (supply mix). Grey electricity

accounts for 98.5% of the "transport medium" process step; 0.7% is caused by direct emissions and the remaining 0.8% by infrastructure and auxiliary materials.

The different transport burdens for the various PtGLS products (B-02 to B-06) are based, on the one hand, on the corresponding energy densities of the products and thus the different volumes to be transported per MJ on the tankers. On the other hand, distribution in Germany by truck is modelled for NH_3, MeOH, DME and FT, while for H_2 and SNG, distribution is assumed to be by gas pipeline. For the transport of SNG by ship, SNG is also burned in the liquefaction plant and used as ship fuel, as is currently common practice for the transport of LNG. These expenses are included as additional SNG requirements of around 10% in the other categories.

Consumables that contribute to the carbon footprint include, for example, catalysts used in electrolysis and synthesis processes. For products with carbon content, a significant proportion of the GHG emissions in this category also come from the production of adsorbents for capturing CO_2 from the air (DAC). The corresponding emissions are most pronounced for the hydrogen carriers MeOH, DME and FT fuel, and to a lesser extent for SNG. **Direct emissions** from synthesis processes contribute significantly less in this category.

The burdens from the provision of **energy for CO_2 capture** play a minor role and are barely visible in the stacked columns.

The **electricity requirements for synthesis** for the various PtGLS products are covered by the MENA RE electricity mix (Table 3) and also account for only a small proportion of the respective total emissions.

The amount of renewable electricity required per MJ of PtGLS product for **electrolysis** in the MENA region differs in the base cases due to the hydrogen requirements of the various process chains. Higher GHG emissions result mainly from the specific efficiencies of converting hydrogen into hydrogen carriers (section 2). In case B-01, additional losses arise from the reconversion of ammonia to H_2. For transport, SNG (B-03) is liquefied, for which it is burned in a turbine in the liquefaction plant. This leads to a higher demand for hydrogen and thus electrolysis electricity.

In the "infrastructure" process step, which covers the construction of all facilities for electrolysis, synthesis and splitting as well as their disposal (end-of-life), there are clear differences between the PtG products. In the case of DME and MeOH products, the infrastructure for synthesis accounts for a higher proportion of the total expenditures, whereas the production of SNG, for example, requires a significantly less complex plant infrastructure.

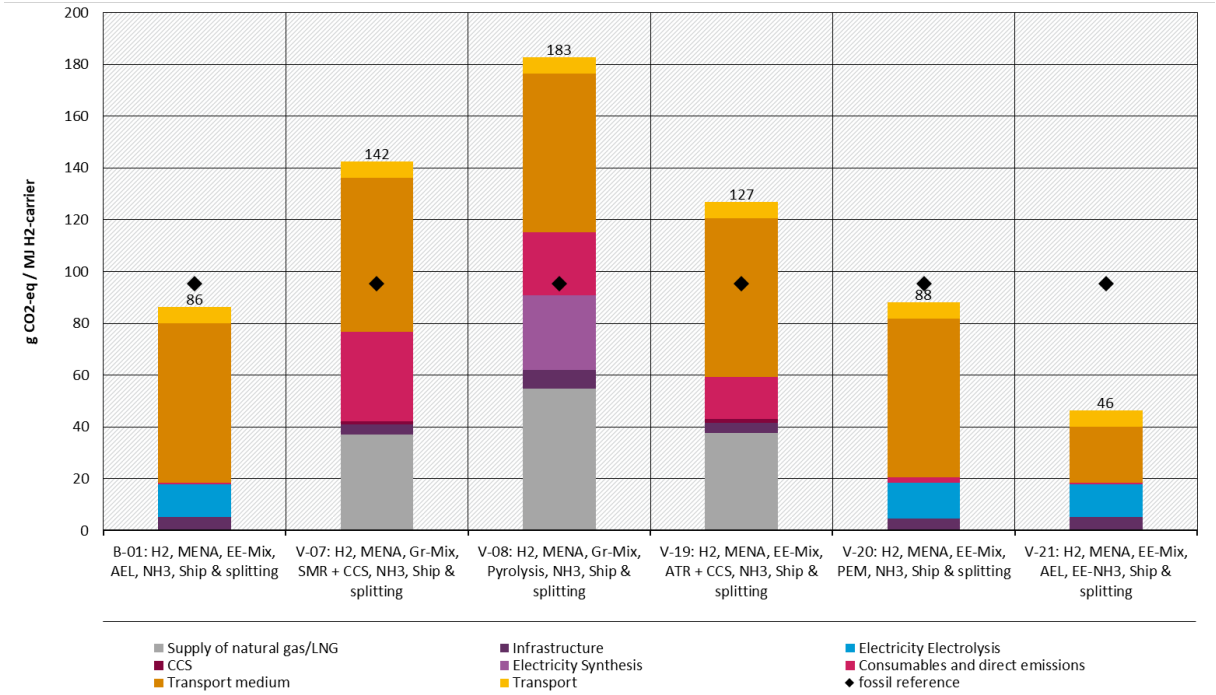
4.3.1.2 Hydrogen variants

In addition to the base case for importing hydrogen to Germany (via NH_3 synthesis and splitting), 15 variants for the supply of H_2 are evaluated. In each of the figures, the base scenario B-01 is shown in the left-hand column for comparison.

Variation in hydrogen production

In five cases (Figure 26), hydrogen production is varied from the base case with green hydrogen from AEL electrolysis. The transport medium ammonia is produced using renewable electricity (V-21). The transport of ammonia to Germany and the subsequent splitting into H_2 remain unchanged.

Figure 26: Carbon footprint of hydrogen (H_2) supply using other production techniques compared to the base case.



Source: own representation, ifeu.

Compared to the fossil fuel reference, cases B-01 and V-20 show a reduction of around 10% and case V-21 around 50%. The other cases are around 30-90% higher.

The base case B-01 and variant V-20 (Figure 26, second from right) differ only in the electrolysis technology used. Since the efficiency of PEMEL electrolysis is lower than that of AEL electrolysis, the emissions caused by the **electricity for electrolysis** are slightly higher. There is also a small difference between these variants in terms of **consumables and direct emissions.** One of the critical consumables in PEMEL electrolysis is the use of iridium as a catalyst. However, the contribution of this process step to the GHG emissions is also very low in V-20.

In contrast, the consumables and direct emissions of "blue" (V-07, V-19) and "turquoise" (V-08) hydrogen products have a significant impact on the respective overall result. Direct emissions and upstream emissions from the provision of steam from natural gas contribute to the respective overall result for SMR and ATR reformers with a good 0.03 kg CO_2 eq./MJ H_2 each. In contrast, the emission of uncaptured CO_2 is significantly higher for SMR technology than for ATR due to the nature of the process, resulting in a visible difference in the GHG results of "blue" hydrogen products. The high emissions of methane pyrolysis in the area of consumables and direct emissions also originate largely from the provision of natural gas. Natural gas is used both for pyrolysis, which produces solid carbon, and for the generation of steam/heat via combustion with the corresponding CO_2 emissions.

The **infrastructure** -related emissions of the variants hardly differ from those of electrolysis in the base case B-01. Only in the case of methane pyrolysis (V-08) the emissions are higher. This is because the material list for the pyrolysis reactor is based on a laboratory-scale pilot plant (Postels et al. 2016) and more accurate data for modelling larger plants is not available.

While the production of "blue hydrogen" (V-07 and V-20) requires hardly any external electricity, methane pyrolysis (V-08) requires electricity for the synthesis (1.28 kWh/kg) and

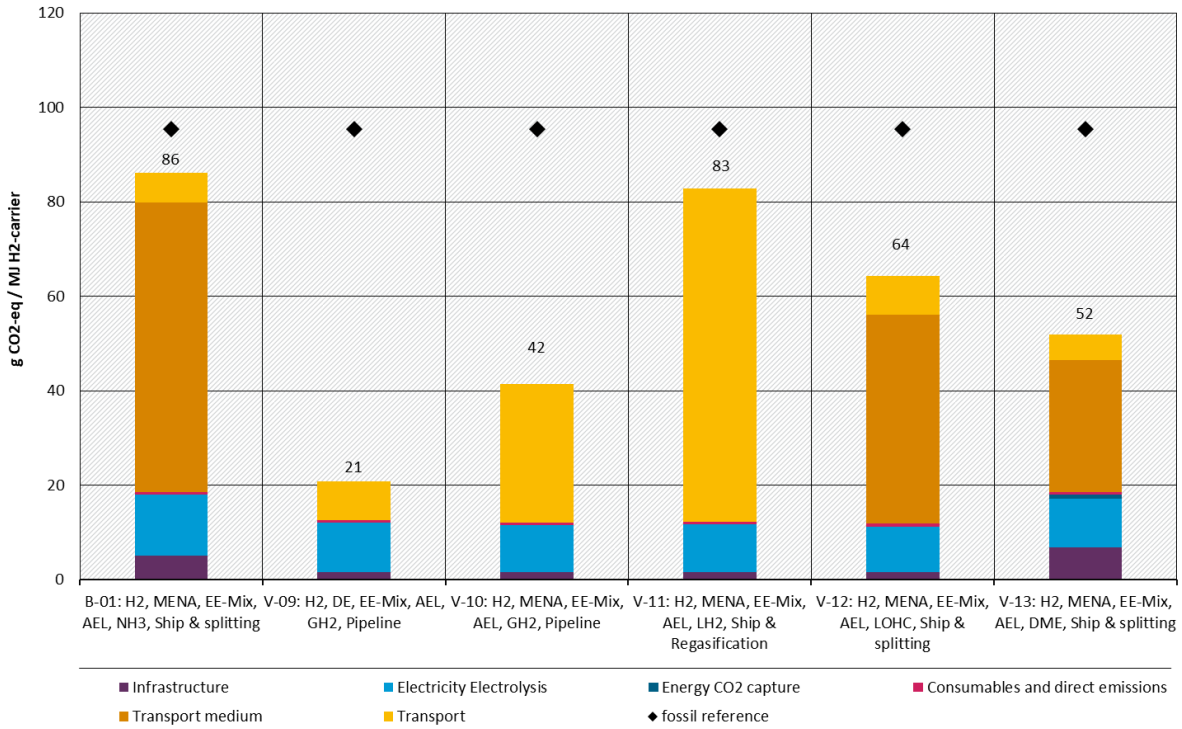
compression (1.93 kWh/kg) of the hydrogen produced to 30 bar. This is clearly visible in the section "**Electricity Synthesis**" in V-08.

If not only electrolysis but also ammonia synthesis (V-21) is powered by renewable electricity, GHG emissions in the **transport medium** group are reduced by approximately two-thirds. This illustrates the strong potential for GHG emission reduction offered by the use of renewable energy sources throughout the value chain – especially in the synthesis and splitting of the transport medium (in this case ammonia).

Variation in hydrogen transport

In five further cases (Figure 27), four different modes of transport are considered instead of transporting green hydrogen as NH_3 by ship: the transport of gaseous H_2 via a gas pipeline (V-10), and the transport of liquefied H_2 (V-11), LOHC (V-12) and DME (V-13) by sea. One variant considers the production of green hydrogen in Germany (V-09), thus international transport routes, conversion into a transport medium and reconversion are dispensable. The LOHC and DME variants each include the reconversion to H_2 in Germany and the return transport of the carbon (carrier) used for conversion to the MENA region. All cases include distribution via gas pipelines in Germany.

Figure 27: Carbon footprint of hydrogen (H_2) supply with different transport options compared to the base case.



Source: own representation, ifeu.

Compared to the fossil fuel reference, case V-09 shows the strongest reduction (around 80%) and case V-11 the lowest (around 15%).

Transport has a significant impact on the overall GHG emissions of hydrogen imported into Germany. This is evident in variant V-09, which has no international transport routes and no need for conversion through **production in Germany**. Infrastructure-related emissions, such as those associated with the H_2-NH_3-H_2 conversions, are also not required here, leaving only a need for infrastructure for electrolysis and transport infrastructure in Germany.

In cases V-10 to V-13, the electrolysis of green hydrogen remains in the MENA region, meaning that transport, transport media and conversion account for a large proportion of total GHG emissions, as in the base case.

In variants V-10 and V-11, green **hydrogen** is transported **as a gaseous or liquefied product**. If the hydrogen is transported in gaseous form and under high pressure via a long gas pipeline from the MENA region to Germany (V-10), the use of non-renewable electricity for compressors along the route plays a major role. These burdens are less than half as high as the transport burdens of liquefied hydrogen by sea (V-11), but at 71% they account for the largest share of the carbon footprint of variant V-10. The emissions of liquid transport almost reach those of transport and transport medium (NH_3) in the base case B-01. Further advantages of hydrogen transport via gas pipeline over the base case are lower H_2 demand (electricity for electrolysis) and the elimination of facilities (infrastructure) for NH_3 synthesis and splitting. A significant improvement could be achieved in all three cases by using renewable energies for ammonia synthesis (see V-21) or for liquefaction or pipeline transport (see also section 5).

In the two right-hand variants in Figure 27, the green hydrogen is not converted into NH_3, but into **LOHC** (V-12) or **DME** (V-13). As in the base case, the conversions of LOHC and DME take place using grid electricity (supply mix) and heat from fossil fuels. Since these processes and the recovery of H_2 from LOHC and DME are less energy-intensive than for NH_3, the results in the "transport medium" category are significantly better for V-12 and V-13 than for B-01. However, these variants would also benefit from the use of renewable electricity for the conversion processes.

In the "transport" category, the different densities of the transport media – in terms of their hydrogen content – play a decisive role (see section 2.14). Per MJ of hydrogen, LOHC therefore incurs the highest transport emissions, followed by NH_3 and DME.

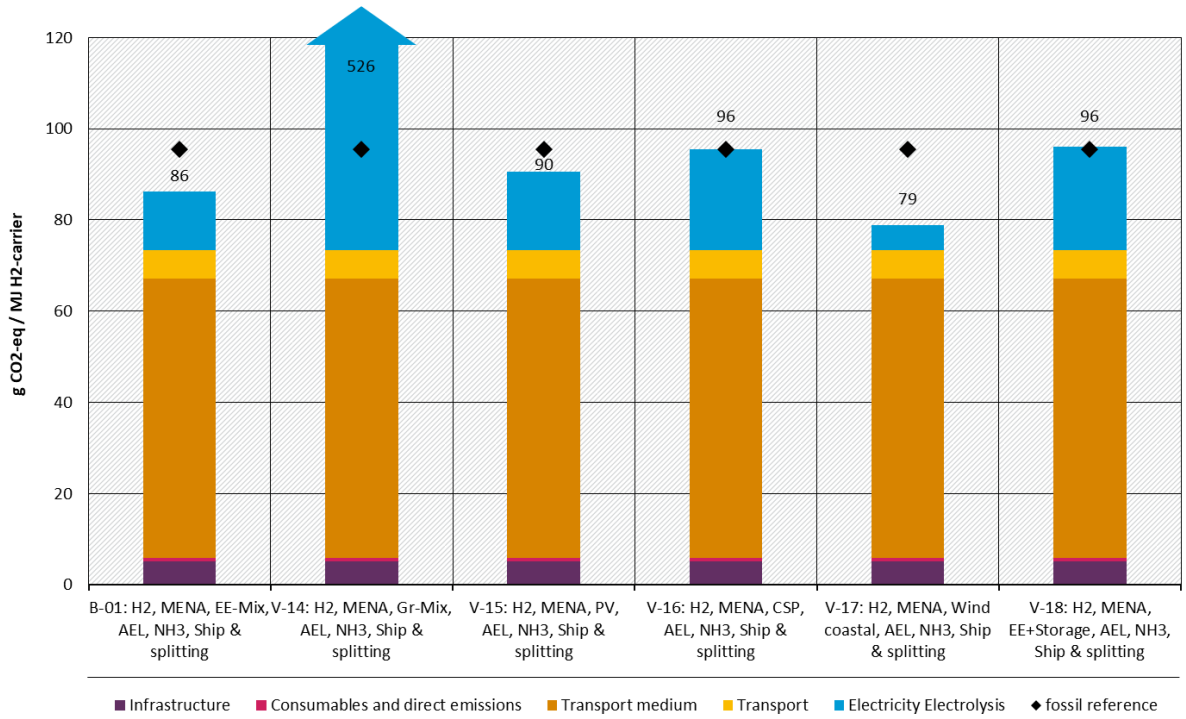
The infrastructure-related emissions from DME production and splitting exceed the infrastructure-related emissions of H_2-NH_3- H_2 conversion in the base case B-01. The emissions from consumables and direct emissions from DME conversion also reduce the advantage of this hydrogen transport medium over LOHC, although the use of both LOHC (V-12) and DME (V-13) for the transport of green hydrogen from the MENA region generates significantly lower GHG emissions overall than the base case via NH_3.

Variation in electricity source

Five additional variants examine the influence of the electricity source for hydrogen electrolysis in the MENA region (Figure 28). The renewable electricity mix of the base case (Table 3) for MENA is replaced by MENA grid electricity, PV electricity, CSP and wind power at coastal locations. In addition, the use of an electricity storage facility for full utilisation of the synthesis plants is considered. The remaining process steps, such as electrolysis and transport as ammonia to DE– including splitting – remain unaffected.

If the hydrogen in the MENA region is not produced using the renewable electricity mix, this only affects the GHG results in the category "**Electricity Electrolysis**". The production of grey electrolysis hydrogen (V-14) with MENA grid electricity (Table 4) significantly increases GHG emissions, based on the high carbon footprint of the electricity mix (822 g/kWh). The carbon footprint is therefore around 550% of the fossil fuel reference.

Figure 28: Carbon footprint of hydrogen (H_2) supply with different electricity generators compared to the base case.



Source: own representation, ifeu.

The remaining variations in renewable electricity in V-15, V-16 and V-17 lead to results that reflect the underlying GHG emissions per kWh of electricity (Table 2). CSP electricity (V-16) shows the highest carbon footprint among the renewable electricity sources considered here. The variant with pure PV electricity use (V-15) shows slightly higher results than the base case B-01, which is based on a mix of PV, CSP and wind power. The variant V-17 with the use of MENA wind power (coastal location) shows the lowest GHG emissions in Figure 28 and is slightly below the base case. Compared to the fossil fuel reference, only minor to very minor reductions are evident.

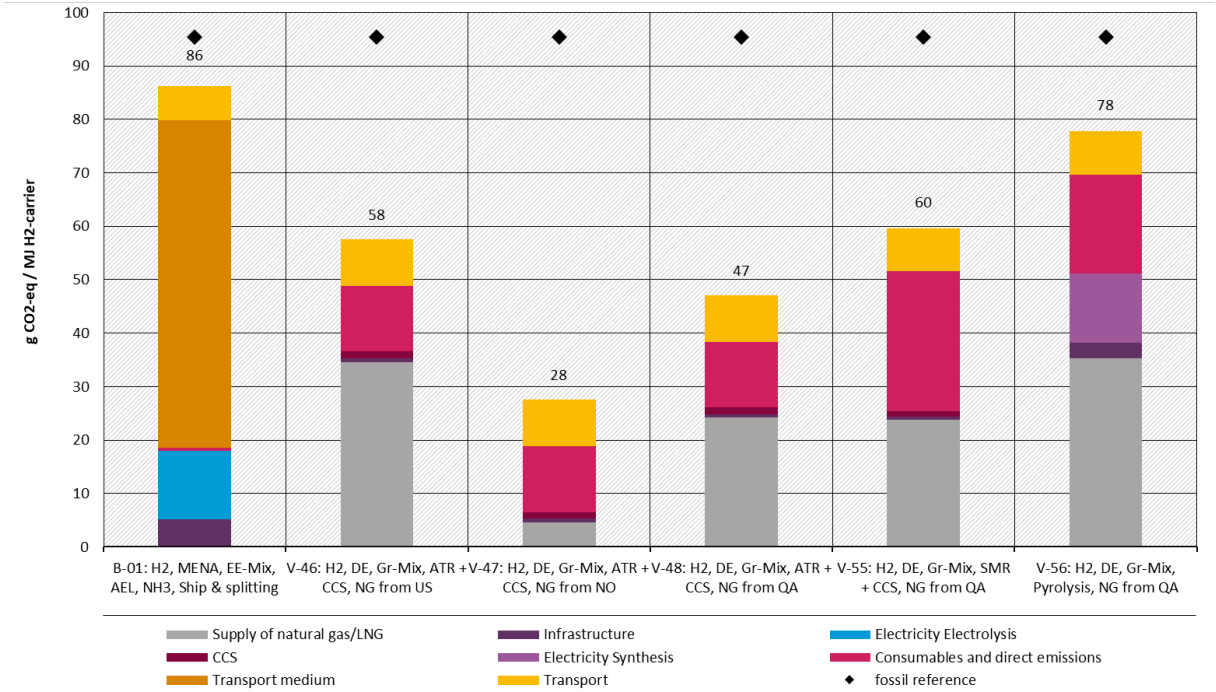
The use of an electricity storage facility (V-18) enables the electrolysis and synthesis plants to operate beyond the specific operating hours of the power generation plants, initially reducing the relative contributions of the infrastructure for PV and wind power plants. However, the materials needed for the electricity storage system cause an additional 36 g CO_2 eq./kWh of electrolysis electricity. As a result, the results for V-18 are around 10% higher than the base case B-01. Effects on maintenance intervals and impacts on service life due to continuous plant operation cannot be taken into account in this analysis.

A consideration of other locations for the provision of hydrogen with different transport distances and full-load hours of electricity generation – Denmark and Spain (Iberian Peninsula) – is provided in the appendix.

Blue and turquoise hydrogen

Variants V-46 to V-48 in Figure 29 show the conversion of natural gas to hydrogen using ATR and CCS in Germany (blue hydrogen). The import of natural gas from different supply countries varies. Variants V-55 and V-56 show the import of natural gas from Qatar and hydrogen production using SMR and CCS (blue hydrogen) or pyrolysis (turquoise hydrogen) in Germany.

Figure 29: Greenhouse gas potential of hydrogen (H_2) supply via ATR/SMR+CCS or pyrolysis in Germany with various countries of supply for natural gas/LNG.



Source: own representation, ifeu.

Compared to the base case and the fossil fuel reference, the results for the variants are more favourable, in some cases significantly so. The pyrolysis of imported natural gas (V-56) shows a reduction of around 20% compared to the reference, while the autothermal reforming (ATR) of Norwegian natural gas (V-47) shows a reduction of around 70%.

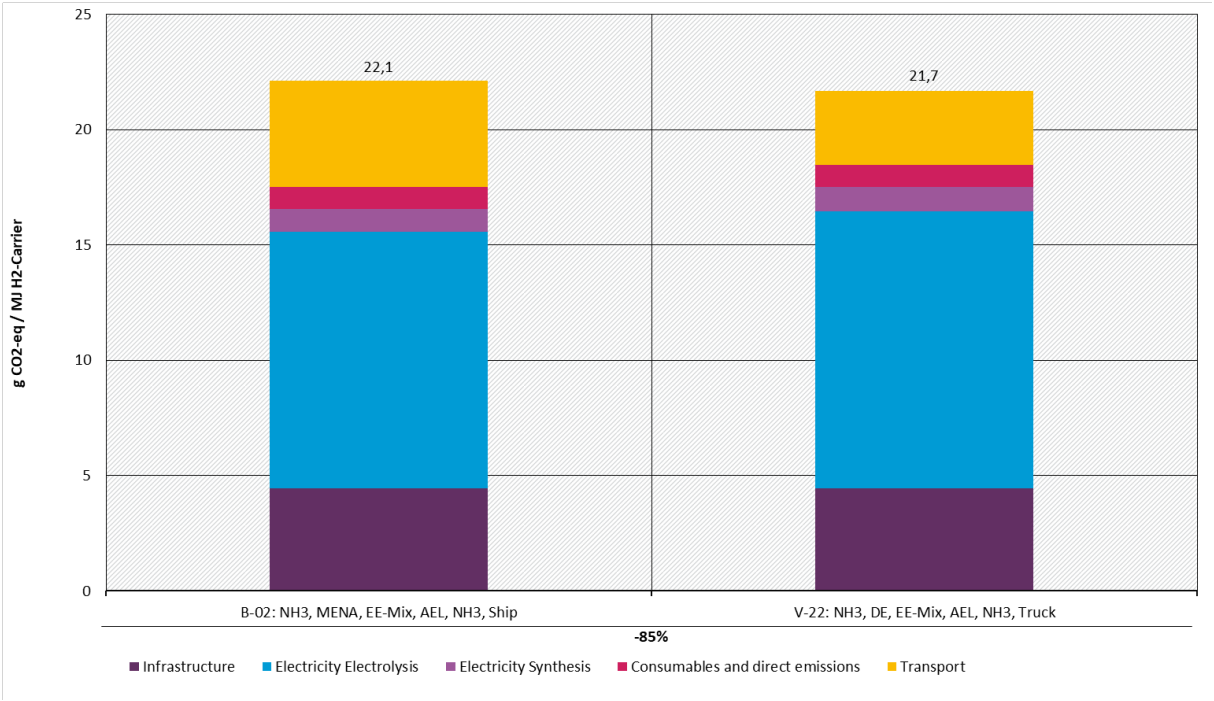
All variants have an advantage over the base case, as no energy-intensive conversion into a transport medium is required. However, extraction, processing and transport to Germany result in emissions from the upstream natural gas chain. For the import of LNG from the USA (V-46), this contribution is 35 g CO_2 eq. /MJ H_2, followed by imports of natural gas from Qatar (V-48) with 24 g CO_2 eq. /MJ H_2 and imports from Norway (V-47) with 5 g CO_2 eq. /MJ H_2. V-47 reflects a high standard of natural gas production that is not achieved in other regions. The contributions from transport also vary depending on the distance to the supplier countries. Overall, importing natural gas from Norway and converting it to hydrogen using ATR in Germany causes only half the climate impact of importing from the USA.

The SMR and pyrolysis routes are at a disadvantage compared to ATR (see Figure 26).

4.3.1.3 Ammonia variants

A variant to the base case was calculated for the provision of ammonia as a PtGLS product. Figure 30 shows the carbon footprint of production with renewable electricity in Germany (V-22).

Figure 30: Carbon footprint of ammonia (NH_3) supply using renewable electricity in Germany compared to the base case.



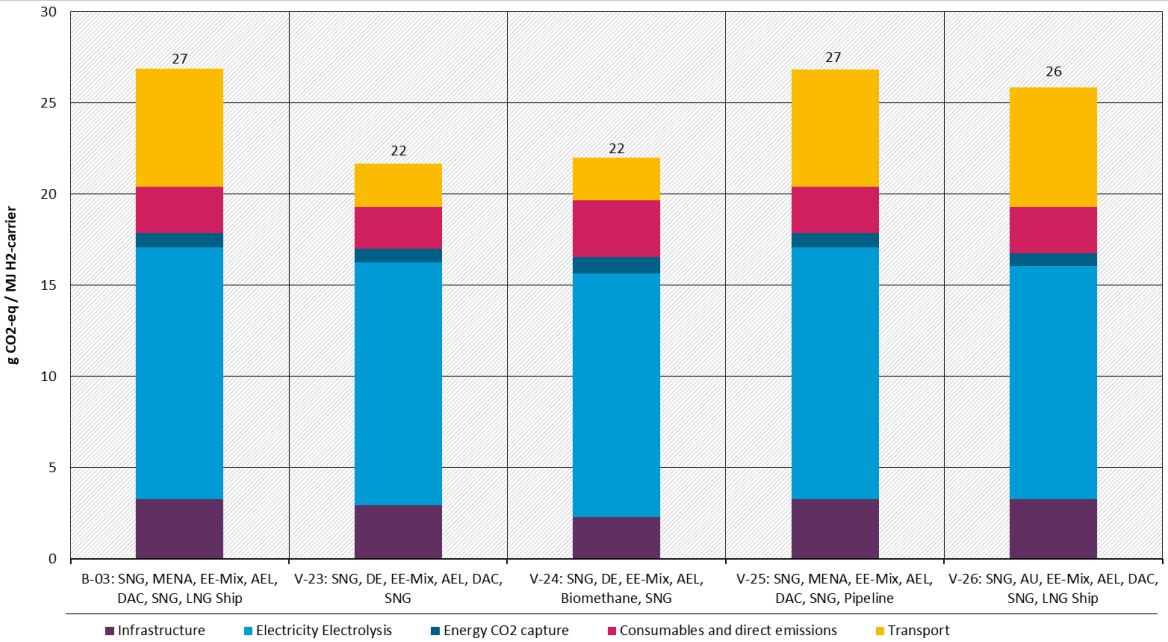
Source: own representation, ifeu.

Production in Germany (V-22) shows almost the same carbon footprint as the baseline case. Since the carbon footprint of the renewable electricity mixes in Germany and the MENA region differ only slightly (see Table 3: 21-25 g CO_2 eq./kWh), the results for electricity for electrolysis and for electricity demand for synthesis are almost the same. The burdens from infrastructure, consumables and direct emissions are identical. The biggest difference between the variant and the base case is in the "transport" category. For variant V-22, ship transport, which accounts for around 40% of the result, is eliminated. The remaining share is caused by transport by truck in Germany.

4.3.1.4 Methane (SNG) variants

Four variants to the base case were calculated for the provision of methane (SNG) as a PtGLS product. Production in Germany was modelled using CO_2 from DAC (V-23) or biomethane (V-24), transport via pipeline from the MENA region (V-25), and production in Australia with corresponding ship transport (V-26).Figure 31 shows the carbon footprint of these variants.

Figure 31: Carbon footprint of Supply of methane (CH_4, SNG) with renewable electricity at various locations and its transport compared to the base case.



Source: own representation, ifeu.

Compared to the fossil fuel reference, which is 69 g CO_2 eq./MJ, reductions of 60% to 70% are evident.

Variants V-23 (production in Germany, CO_2 from DAC) and V-24 (production in Germany, CO_2 from biomethane production) show the best results. Compared to the base case (production in the MENA region and transport by ship over 4,000 km), the carbon footprints are around 20% lower. The results for the other variants hardly differ from the base case in terms of the total amount.

The biggest differences are in the **"transport"** category. These are mainly due to the efforts needed for liquefaction and regasification, as well as methane emissions from ship and gas pipeline transport. Part of the energy related emissions for transport are also included in the other categories, as both the liquefaction plant and the pipeline compressors are powered by the transported gas, as is currently standard practice for natural gas. For liquefied methane (B-03 and V-26), this accounts for around 10% of the emissions in the categories other than transport, and for pipeline transport (V-25) around 5%.

However, the differences in GHG intensities of the renewable electricity mixes used are minor and have little impact on the result (see Table 3: 21-25 g CO_2 eq./kWh).

Production in the MENA region with subsequent transport via gas pipeline over 3,000 km (V-25) incurs similar emissions for compression as liquefaction in the base case B-03. From this, it can be generalised that this distance is approximately the "break-even point". For distances shorter than 3,000-4,000 km, transport via gas pipeline is associated with lower climate impacts, while for longer distances, transport by ship is associated with lower climate impacts. In the case of production in Australia (V-26), the slightly lower impacts of the local renewable electricity almost offset the higher transport impacts.

Production in Germany with CO_2 from biomethane production (V-24) has lower impacts from transport and infrastructure, but additional emissions from the energy required for CO_2

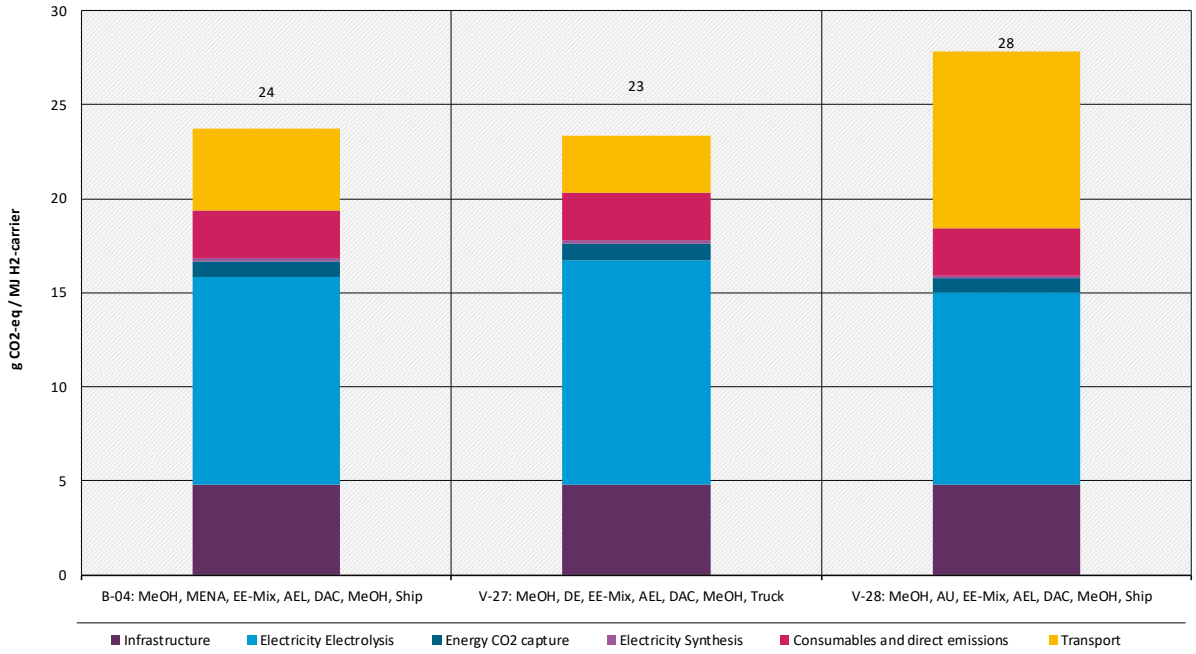
separation. These are mainly related to electricity and heat, but increased proportions of consumables and methane emissions also result in higher impacts.

A consideration of another region (SNG with wind power from Canada) can be found in the appendix.

4.3.1.5 Methanol variants

In addition to the base case for the import of methanol (MeOH) from the MENA region to Germany, two variants of production with renewable electricity in different regions (Germany and Australia) are evaluated.

Figure 32: Carbon footprint of the supply of methanol (MeOH) with renewable electricity at different locations and its transport compared to the base case.



Source: own representation, ifeu.

Overall, the results for V-28 (production in Australia) are about 15% higher than the baseline scenario, while German MeOH production (V-27) enables a slight reduction in greenhouse gas emissions compared to MeOH from the MENA region. However, in relation to the fossil reference of 114 g CO_2 -eq./MJ, the results are 75–80% lower.

The GHG emissions from infrastructure, CO_2 capture and consumables/direct emissions remain unaffected by the change in production location. The results of the variants differ in the process steps "transport" and "electricity electrolysis". In terms of **transport**, truck distribution within Germany accounts for a large proportion of transport emissions; the same transport distances within Germany are modelled for all variants. In the base case, the GHG emissions from truck transport in Germany are more than twice as high as those from ship transport between MENA and Germany. The emissions for the Australia-Germany sea route are almost five times higher than in the baseline case (sea routes 19,000 km to 4,000 km), in line with the transport distance. In the base case, transport-related emissions contribute around 20% to the overall result, around 15% for production in Germany (V-27) and around 35% for imports of Australian MeOH.

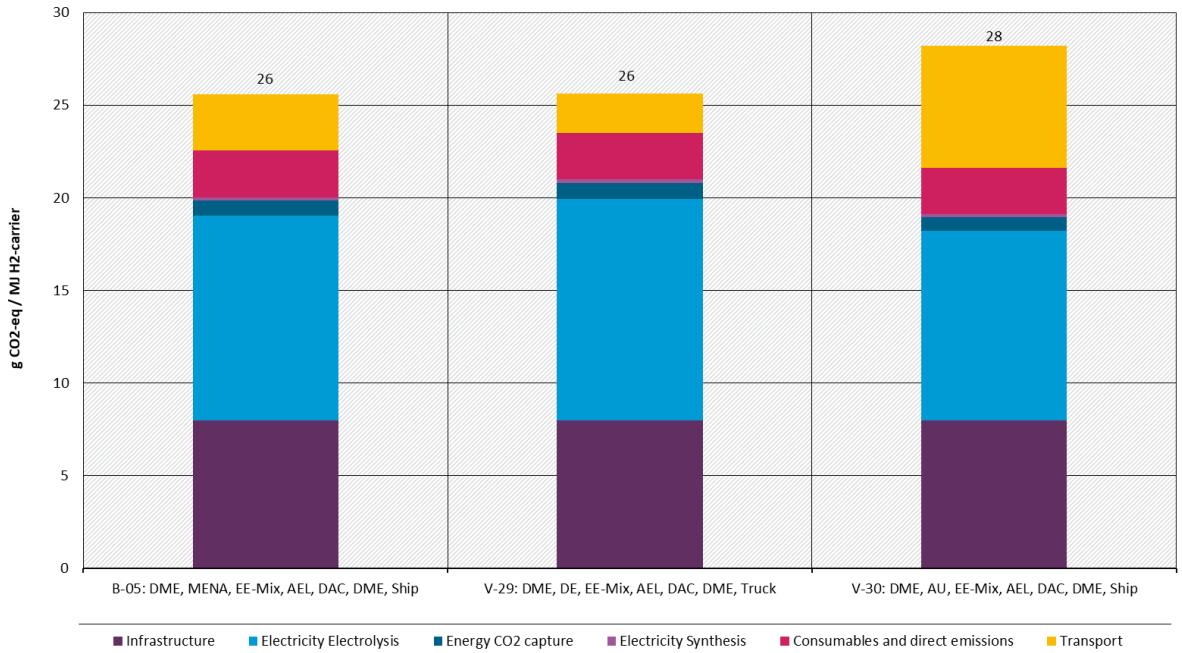
The slight differences in the carbon footprints of **the electricity used for electrolysis** result from the different carbon footprints of the renewable electricity mixes in the production regions (see Table 3: 21-25 g CO_2 eq./kWh).

A consideration of other locations (South Africa and Chile) can be found in the appendix.

4.3.1.6 Dimethyl ether variants

The import of DME from the MENA region to Germany was supplemented by two variants that consider production with renewable electricity in different regions (Germany and Australia).

Figure 33: Carbon footprint of supplying dimethyl ether (DME) with renewable electricity at various locations and transporting it to Germany compared to the baseline scenario.



Source: own representation, ifeu.

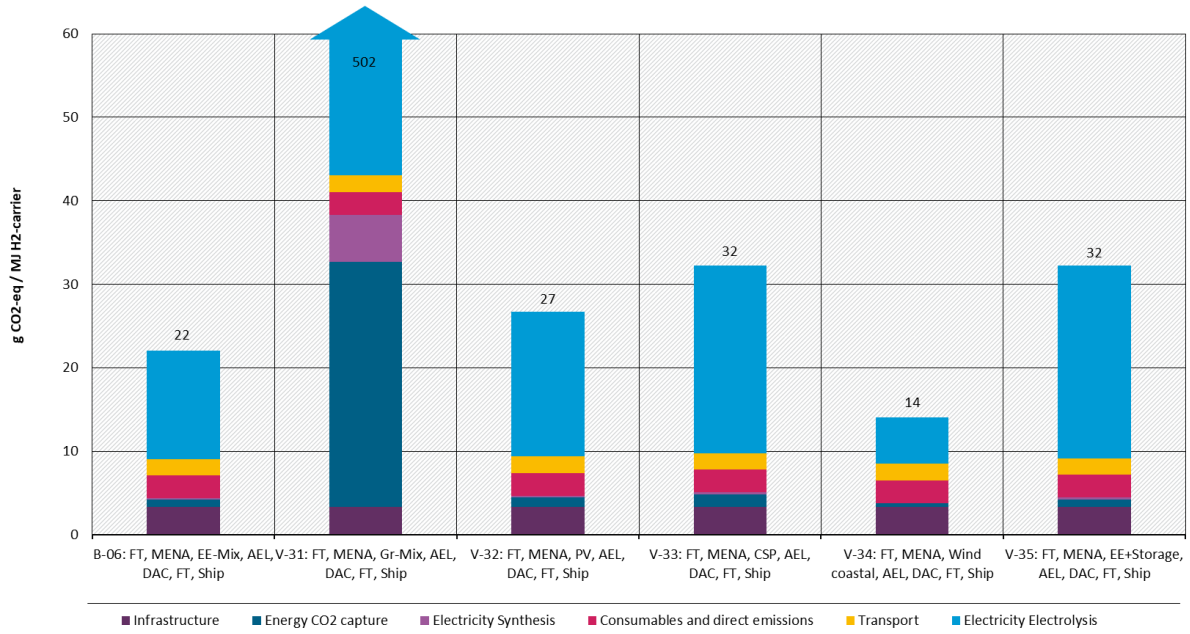
The changes observable for the variants of DME production countries are basically similar to those already described for MeOH. In contrast to MeOH production, however, the infrastructure involved in DME production contributes an even greater share to the overall impact (around 30%), while transport contributes less significantly than for MeOH in both relative and absolute terms. The latter is due to the higher calorific value of DME and thus lower specific transport volume (Table 23).

The results are around 75–80% below the fossil reference value of 119 g CO_2 eq./MJ. Due to the high infrastructure burdens, which do not vary from region to region, both the advantages and disadvantages of production in Germany/Australia are lower than for MeOH. The burdens of German DME production (V-29) are similar to DME imports from MENA. Despite the sea route being five times longer, imports from Australia (V-30) result in only 7% higher GHG burdens per MJ of DME compared to the base case MENA. The carbon footprint of the process steps "infrastructure", "CO_2 capture" and "consumables and direct emissions" are the same for the base case, V-29 and V-30.

4.3.1.7 Variants petrol/diesel/kerosene/naphtha

For Fischer-Tropsch fuels, hydrogen production in the MENA region was varied using different electricity sources. In addition to the use of grid electricity from the supply mix (V-31), three renewable electricity generators were modelled: pure PV electricity (V-32), concentrated solar power (CSP) (V-33) and wind at coastal locations (V-34). In addition, the use of an electricity storage facility for full utilisation of the synthesis plants is considered (V-35). The base case represents a mixture of the electricity generators from V-32 to V-34 according to Table 3.

Figure 34: Carbon footprint of the provision of Fischer-Tropsch fuels (FT) with different electricity generators compared to the base case.



Source: own representation, ifeu.

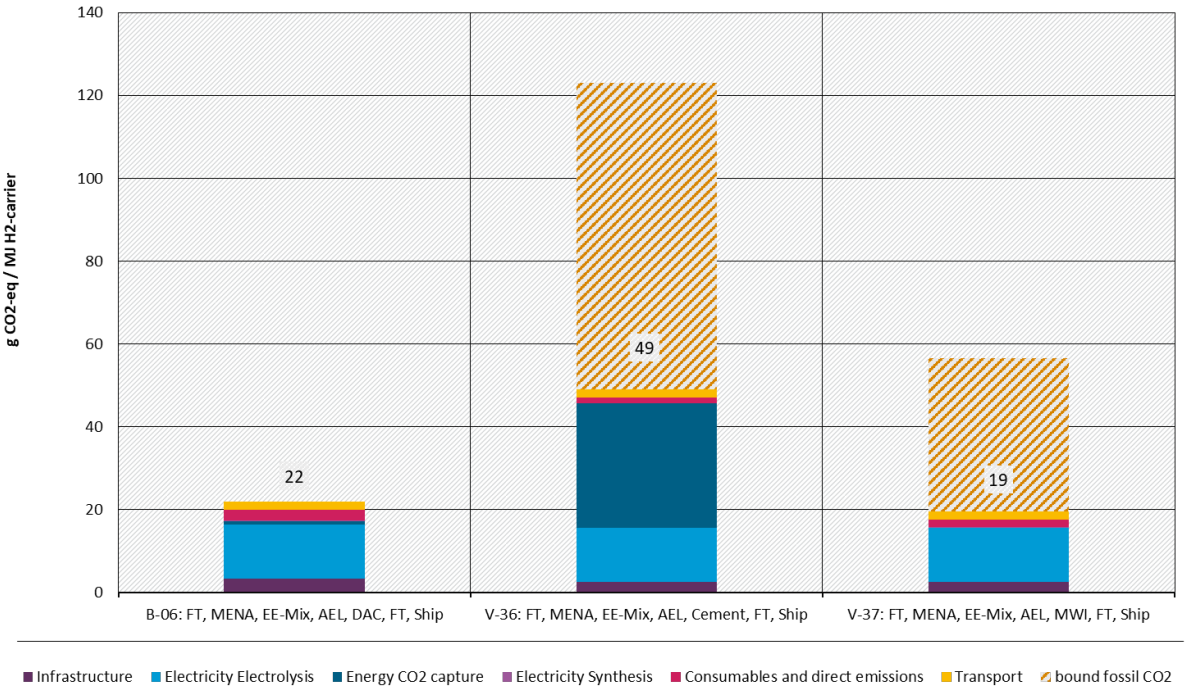
In the base case for FT fuels, electricity generation for water electrolysis already accounts for around 60% of the total result of GHG emissions. A variation in this process step has a correspondingly strong influence on the result.

If FT fuels from the MENA region are imported into Germany that have been synthesised on the basis of electrolysis hydrogen from grid electricity (supply mix) (V-31), the climate impact per MJ of FT fuel is around 23 times higher than in the base case (RE mix MENA) and 5 times higher than the fossil reference. In this case, the electricity for electrolysis accounts for over 90% of the climate impact of the fuel. The results of the further variations in renewable electricity in V-32/V-33/V-34 are based on the underlying carbon footprints per kWh of electricity (Table 2). CSP electricity (V-33) shows the highest carbon footprint among the renewable electricity sources considered here. The use of pure PV electricity (V-32) shows results that are around 20% higher than in the base case B-06, which is based on a mix of PV, CSP and wind power. Variant V-34 with wind power (coastal location) shows the lowest GHG emissions among the variants and is around 35% below the base case. This is due to the low carbon footprint of wind power and the high proportion of PV power in the renewable energy mix (see Table 2 and Table 3 in section 2.1). The results of cases V-32/V-33/V-34 are around 65–85% below those of the fossil fuel reference.

The use of an electricity storage facility (V-35) enables continuous operation of the electrolysis and synthesis plants beyond the specific operating hours of the power generation plants.

However, the material related emissions for the electricity storage system cause an additional 36 g CO_2 eq. per kWh of electricity. Taken together, the impact for V-35 is higher than almost all variants for renewable electricity sources and around 50% higher than the base case B-06.

Figure 35: Carbon footprint of the provision of Fischer-Tropsch fuels (FT) with different CO_2 sources compared to the base case.



Source: own representation, ifeu.

Variation in CO_2 source

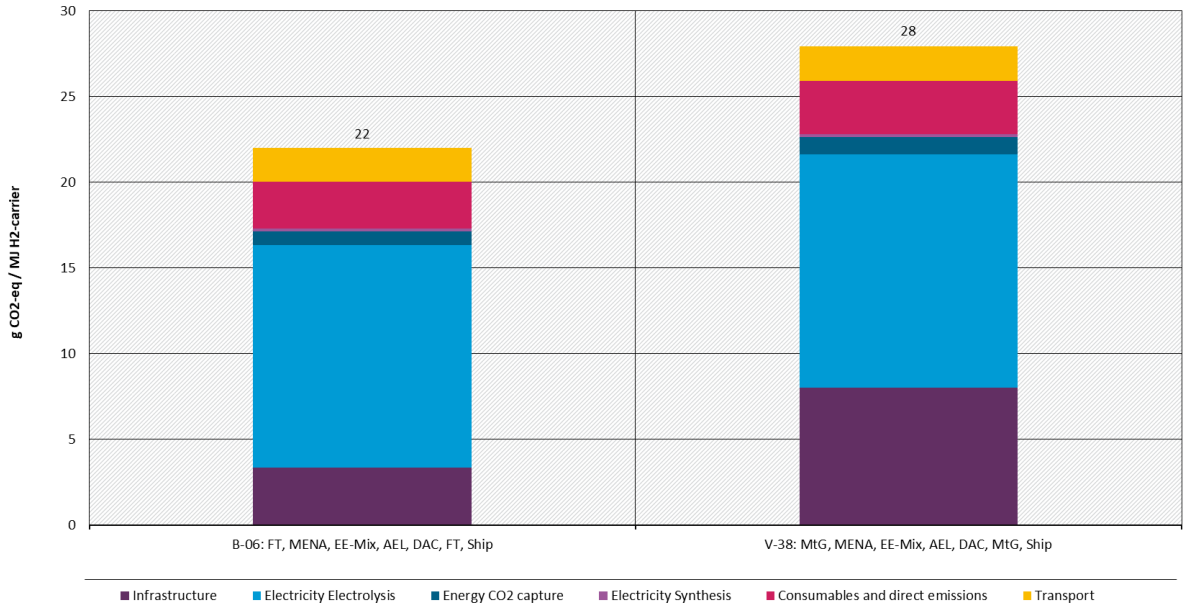
Other variants of FT fuel production in the MENA region relate to the source of the carbon used in FT synthesis. In addition to extraction from ambient air (DAC), CO_2 from cement production or waste incineration is also considered.

While the result of the base case (B-06) is around 75% below that of the fossil reference, the variant with CO_2 from a cement plant (V-36) only achieves a reduction of around 50%. The V-37 variant (capture of CO_2 from a waste incineration plant) is around 80% below the fossil fuel reference.

Among the assumptions made in this study for the energy supply for CO_2 capture (section 2.5) and the allocation of the burdens of the captured carbon (section 4.1.3), variant V-36 performs significantly worse than the base case. Capture at the point sources cement plant and waste incineration plant takes place using monoethanolamine (MEA). To this end, grid electricity from the supply mix and heat from fossil fuels are used in the cement plant. The burdens in the **"Energy CO_2 capture"** category are correspondingly high**.** Electricity and heat in the waste incineration plant (V-37) are supplied by the power plant and are burden-free, as emissions from the waste incineration plant are allocated to waste recycling as a service. This results in a reduction of approximately 10% compared to the base case. The base case shows slightly higher values in the category **"consumables and direct emissions"**. In the base case, these burdens are mainly attributable to the production of the adsorbent material for DAC and, in the variants, to the production and disposal of MEA.

In variants V-36 and V-37, the fossil CO_2 content in the FT product is also shown (hatched segments). This amounts to 74 g CO_2/MJ FT product if the CO_2 originates from the cement plant. In waste incineration plants, half of the CO_2 comes from biogenic sources and half from fossil sources. Therefore, the fossil content is 37 g CO_2/MJ FT product. If the FT fuel were produced in Germany using the same CO_2 sources (not shown), all categories involving electricity consumption (electrolysis, synthesis, CO_2 capture) would deteriorate slightly, but the transport loads would be lower. Overall, the results for the variants would be similar in Germany.

Figure 36: Carbon footprint of petrol supply via the MtG route compared to the base case (Fischer-Tropsch).



Source: own representation, ifeu.

Variation Synthesis

One variant for producing petrol is to use the methanol-to-gasoline (MtG) synthesis route. Both petrol and diesel or kerosene can be obtained from the FT process. Since the production emissions are allocated on the basis of calorific value, FT petrol can be compared directly with MtG petrol. Figure 36 shows the greenhouse gas potential of this process route (V-38) compared to the base case. The loads for MtG petrol are around 30% higher. This is mainly due to the higher contribution of infrastructure, in particular methanol production. The burdens for consumables are also almost twice as high in the MtG route as in the base case. This is due to the water requirements of methanol synthesis, which are difficult to meet in the arid MENA region.

The reduction compared to the fossil reference of 99 g CO_2 eq./MJ is between 70 and 80%.

Another variant for FT fuels from South Africa can be found in the appendix.

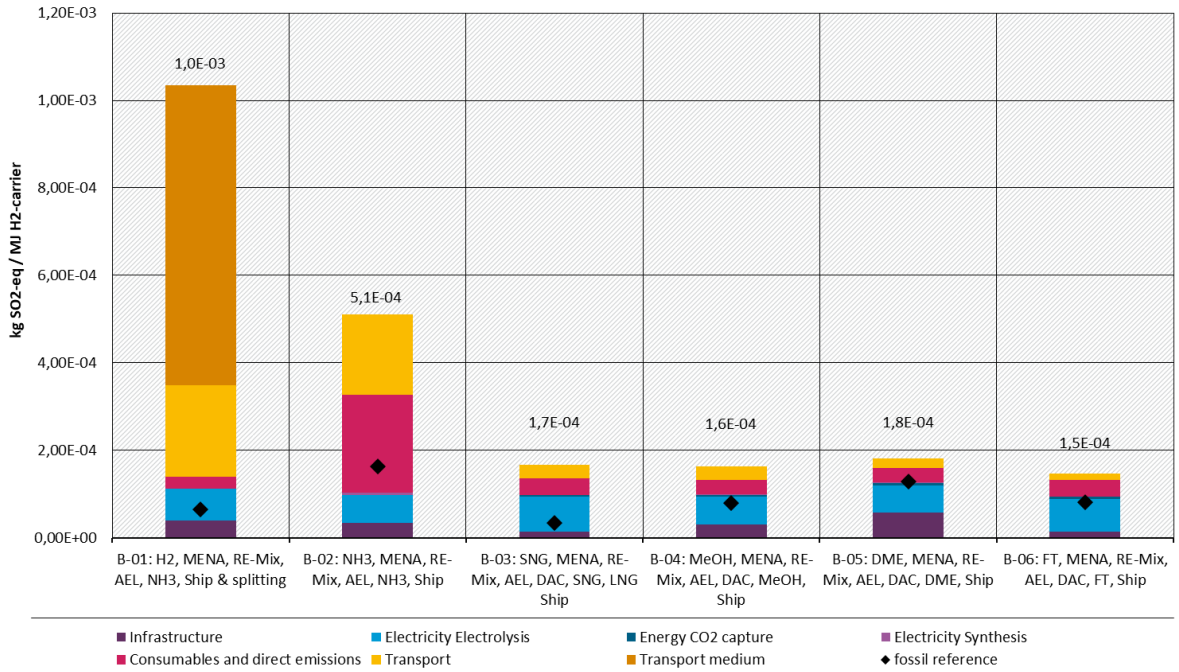
4.3.2 Other environmental impact categories

The following sections present and describe the base cases of the PtGLS products as examples of the other environmental impact categories that are evaluated in addition to carbon footprint.

4.3.2.1 Acidification

Figure 37 shows the results for the acidification potential of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. The stacked columns show the contributions of the process stages according to Table 24.

Figure 37: Acidification potential of the provision of PtGLS products in the base case



Source: own representation, ifeu.

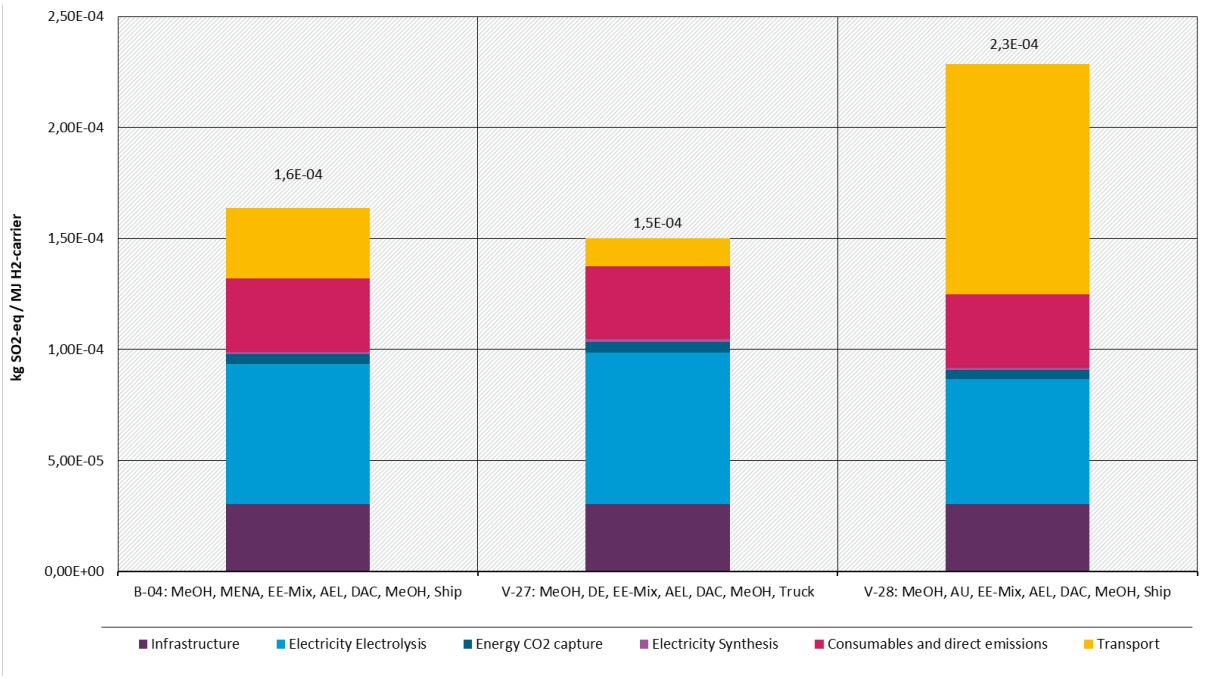
All base cases show a significant increase compared to the respective fossil reference. For case B-01 (H_2 via NH_3), the acidification potential is around 16 times higher than the reference, and for case B-02 (NH_3), it is around three times higher. The provision of synthetic natural gas (B-03) has an acidification potential around five times higher than that of fossil fuels. For DME (B-05), methanol (B-04) and FT fuels (B-06), the results are between 40 and 100% higher than the reference.

The high contribution in the case of hydrogen transported in the form of ammonia (B-01) in the "transport medium" category is striking. Around 40% of this contribution is caused by emissions of ammonia and nitrogen oxides, which are emitted during the production and splitting of ammonia. This is where cases B-01 and B-02 differ: in the latter, ammonia is the target product, not the transport medium. Therefore, emissions for B-02 from ammonia synthesis are listed in the **"consumables and direct** emissions" category and not in the "transport medium" category, as in B-01. This comparison shows that the assumed direct emissions from ammonia cracking could contribute about half of all contributions to acidification.

The contributions to acidification in all other cases are mainly caused by emissions of sulphur dioxide, nitrogen oxides and, to a lesser extent, ammonia from combustion processes. These contributions can be found in the background processes in the production of "infrastructure", in the production of energy generation plants (**"electricity electrolysis")** in **"consumables and direct emissions**" and in "**transport"**. Electricity demand and background processes are generally responsible for over 95% of emissions in this impact category (unless the pathway contains ammonia as a product or transport medium).

Another result is shown in Figure 38, which illustrates the influence of transport distance using methanol as an example. In the "transport" category, there is a linear relationship between transport distance and contribution to acidification, which in the case of Australia as the country of origin accounts for almost half of the environmental impact. As in the base case B-04, both variants are above the fossil reference (approx. 90% (V-27) and approx. 190% (V-28) respectively).

Figure 38: Acidification potential of methanol (MeOH) supply with different transport distances



Source: own representation, ifeu.

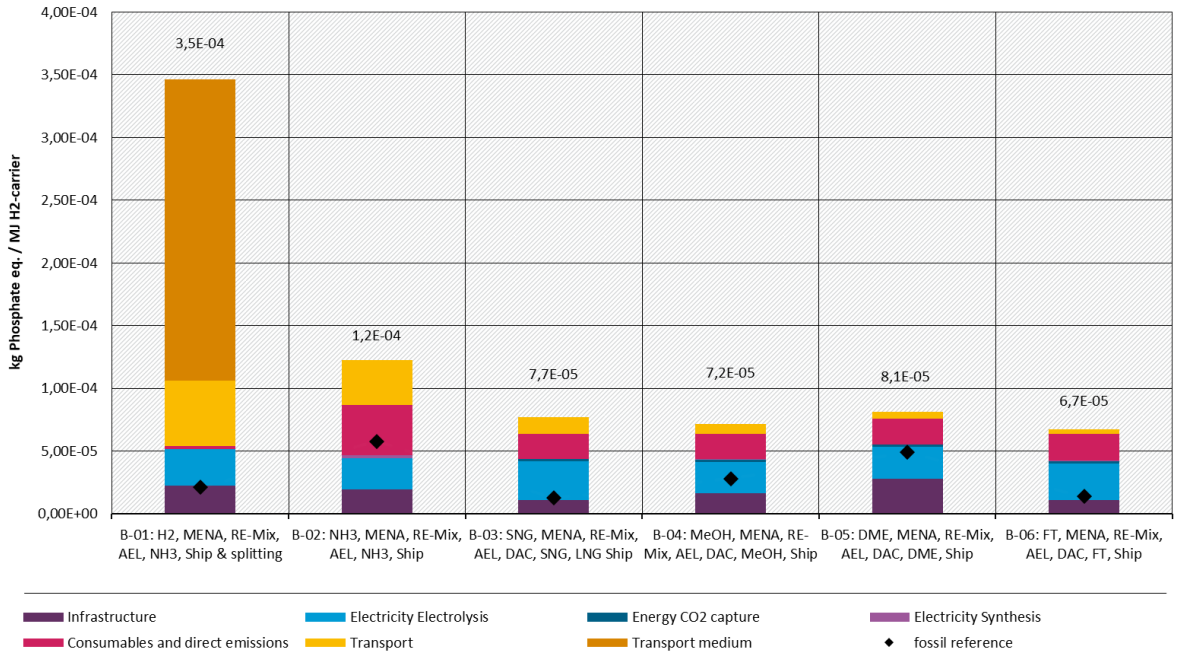
4.3.2.2 Eutrophication

Figure 39 shows the potential for eutrophication (overfertilisation) caused by the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. The stacked columns show the contributions of the process stages according to Table 24. Essentially, the contributions to the eutrophication potential are similar to the results for the acidification potential. The eutrophication potential is also largely caused by emissions of ammonia and NO_X. However, phosphate emissions into water are also added, whereas sulphur dioxide plays no role. This reduces the influence of transport.

Here, too, all base cases show a significant increase compared to the respective fossil reference. For case B-01 (H_2 via NH_3), the eutrophication potential is around 16 times higher, and for case B-02 (NH_3), it is around twice as high as the reference. The provision of synthetic natural gas (B-03) is potentially around six times more eutrophicating than fossil fuel. For DME (B-05), methanol (B-04) and FT fuels (B-06), the results are between 70 and 380% above the reference.

In the "transport medium" category, phosphate emissions into groundwater contribute to direct emissions from ammonia synthesis and splitting. These emissions originate in particular from lignite mining, as the model assumes that German grid electricity is used for ammonia splitting.

Figure 39: Eutrophication potential of the provision of PtGLS products in the base case

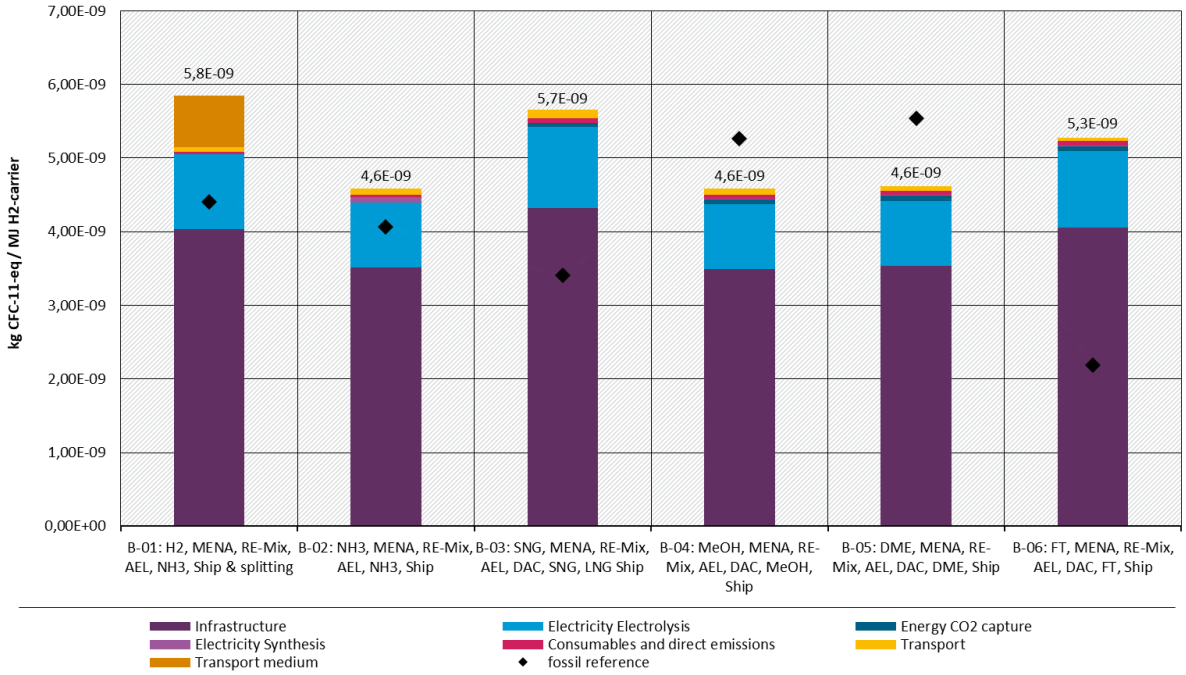


Source: own representation, ifeu.

4.3.2.3 Ozone depletion

Figure 40 shows the results for the potential of stratospheric ozone depletion through the provision of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. There are only minor differences between the cases. The main contribution comes from the **"Infrastructure"** category, specifically from the manufacture of electrolysers. Tetrafluoroethylene is used in the production of the membrane. For base case B-01, ozone-depleting emissions (halon 1301) from the generation of grid electricity contribute significantly to the category **"Transport medium"**. This electricity is used here to synthesise ammonia as a transport medium and to split it again in Germany. Halon emissions from the manufacture of the equipment are also responsible for the ozone-depleting potential **of the "electricity electrolysis" transport medium.**

Figure 40: Ozone depletion potential of the provision of PtGLS products in the base case



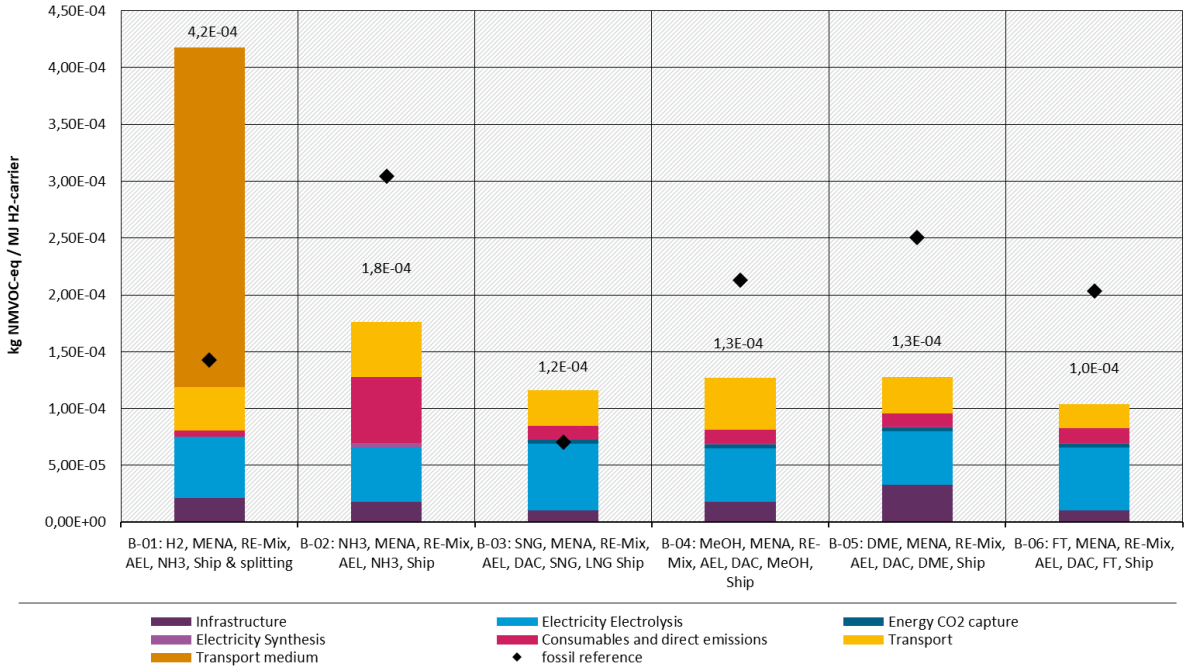
Source: own representation, ifeu.

A comparison with the respective fossil fuel reference shows an inconsistent picture. In case B-01 (H_2 via NH_3), the ozone depletion potential is around 30% higher than the reference, while in case B-02 (NH_3), it is around 15% higher. The provision of synthetic natural gas (B-03) is around 70% more harmful to the ozone layer than fossil fuels. For methanol (B-04) and DME (B-05), the results are around 15% below the reference. FT fuels (B-06) show an ozone depletion potential that is 2.5 times higher than the reference.

4.3.2.4 Summer smog

Figure 41 shows the results for the potential to form summer smog by the provision of the considered PtGLS products in the base cases, each based on 1 MJ calorific value. For base case B-01, the **"transport medium"** category contributes around 70% to the result. This is mainly due to emissions (NO_X, SO_2) during splitting and the use of grid electricity. These direct emissions account for approximately 30% of total emissions. For all base cases, the categories **"transport"** and **"electricity electrolysis"** contribute significantly, mainly through NO_X emissions. For base case B-02, nitrogen emissions from NH_3 production lead to increased results in the category **"consumables and direct emissions".**

Figure 41: Summer smog formation potential of the provision of PtGLS products in the base case



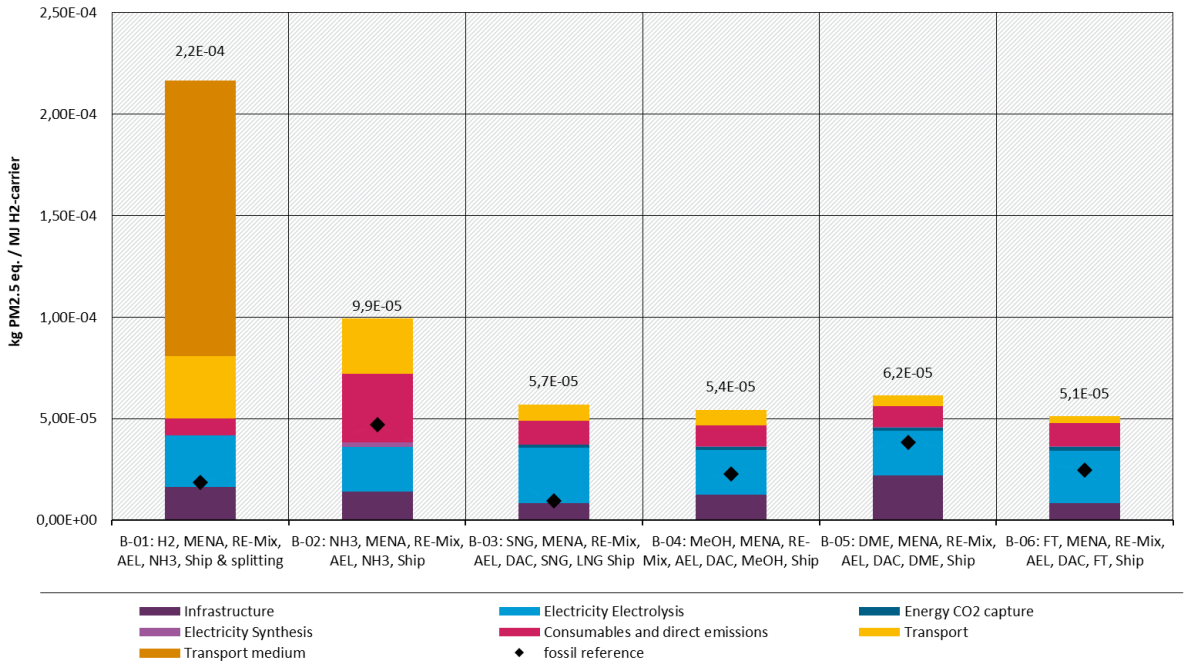
Source: own representation, ifeu.

Compared with the respective fossil fuel reference, the summer smog potential shows a similar picture to the ozone depletion potential. In case B-01 (H_2 via NH_3), the summer smog potential is around three times higher than the reference, while in case B-02 (NH_3), it is around 40% lower. The provision of synthetic natural gas (B-03) is around 60% more harmful to the ozone layer than fossil fuels. For methanol (B-04), DME (B-05) and FT fuels (B-06), the results are around 40–50% below the reference.

4.3.2.5 Particulate matter

Figure 42 shows the results for the potential for particulate matter formation through the provision of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. For base case B-01, the category **"Transport Medium"** contributes around 60% to the result. This is mainly due to direct and indirect (NO_X, SO_2) emissions from NH_3 splitting and the use of grid electricity. Direct emissions account for approximately 25% of total emissions. For all base cases, the categories **"transport"** and **"electricity electrolysis"** contribute significantly, mainly through NO_X emissions. For base case B-02, NH_3 emissions from NH_3 production lead to increased results in the category **"consumables and direct emissions".**

Figure 42: Particulate matter formation potential of the provision of PtGLS products in the base case



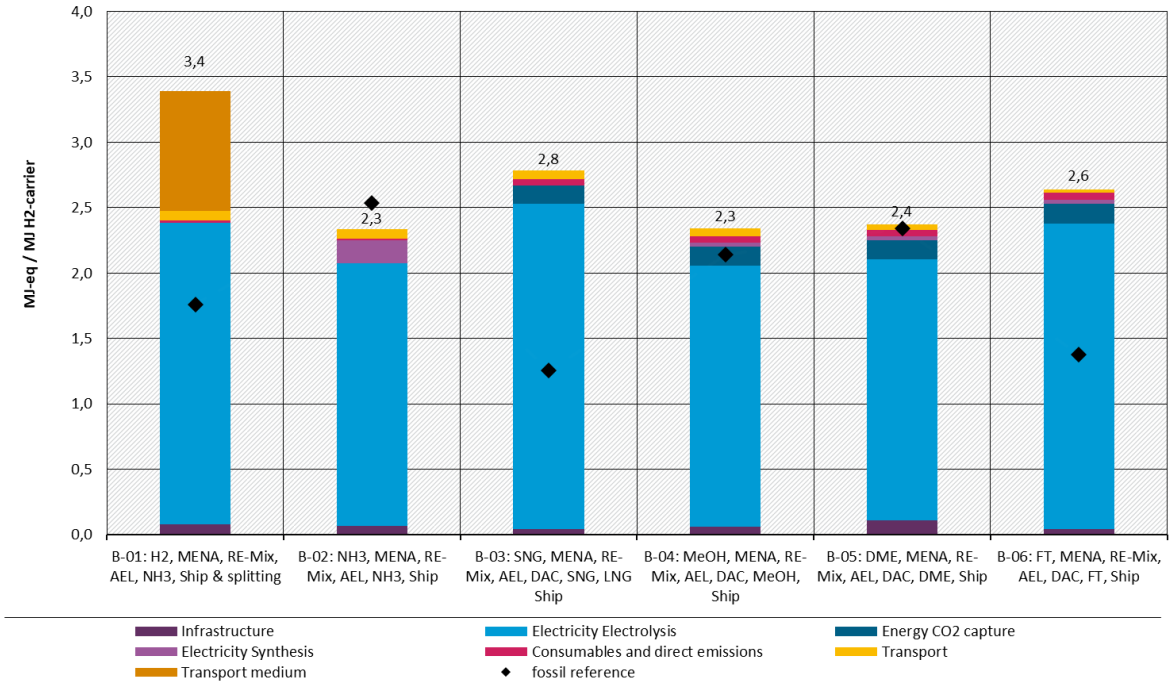
Source: own representation, ifeu.

The results of the base cases are all higher than those of the respective fossil fuel reference. For case B-01 (H_2 via NH_3), the particulate matter formation potential is around 12 times higher than the reference, and for case B-02 (NH_3), it is around twice as high. The provision of synthetic natural gas (B-03) has the potential to generate around 6 times as much particulate matter as fossil fuel. For DME (B-05), methanol (B-04) and FT fuels (B-06), the results are around 60–140% higher than the reference.

4.3.2.6 Cumulative energy demand (CED)

Figure 41 shows the results for the cumulative energy consumption (HHV = calorific value) of the supply of the PtGLS products considered in the base cases, each based on 1 MJ calorific value. The results of all base cases are close to each other. By far the largest contribution is made by the category **"Electricity electrolysis"**. Only in case B-01 are around 30% of the energy demand used for the synthesis and splitting of the **transport medium** ammonia. All other categories contribute only insignificantly to the CED.

Figure 43: Cumulative energy consumption for the provision of PtGLS products in the base case



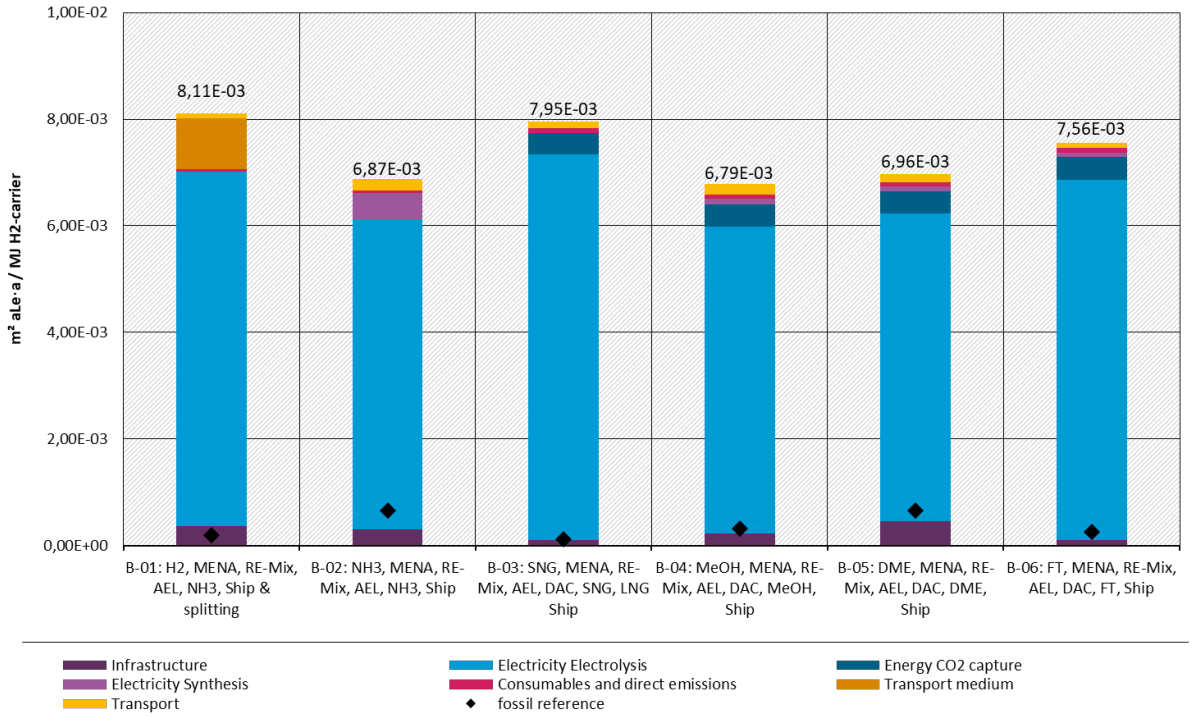
Source: own representation, ifeu.

A comparison with the respective fossil fuel reference shows an inconsistent picture. In the case of B-01 (H_2 via NH_3), the cumulative energy consumption is around twice as high as the reference, while in the case of B-02 (NH_3) it is around 10% below this. The provision of synthetic natural gas (B-03) is around twice as energy-intensive as that of fossil fuel. For methanol (B-04), the result is 10% below the reference, and for DME (B-05) it is almost on a par with it. FT fuels (B-06) show a cumulative energy consumption that is around 90% higher than the reference.

4.3.2.7 Hemerobic-weighted land use

Figure 44 shows the results for hemerobically weighted land use through the provision of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. Here, too, the results of all base cases are close to each other. Once again, the category **"electricity electrolysis"** makes by far the largest contribution. Only in case B-01 does around 10% of the hemerobic-weighted land use arise from grid electricity for the synthesis and splitting of the transport medium ammonia, which is attributed to the "transport" category.

Figure 44: Hemeroby of the provision of PtGLS products in the base case



Source: own representation, ifeu.

The results of the base cases are between 10 and 70 times higher than those of the respective fossil fuel reference. The reason for this is the land required for power generation plants, especially PV.

4.3.2.8 Water requirements

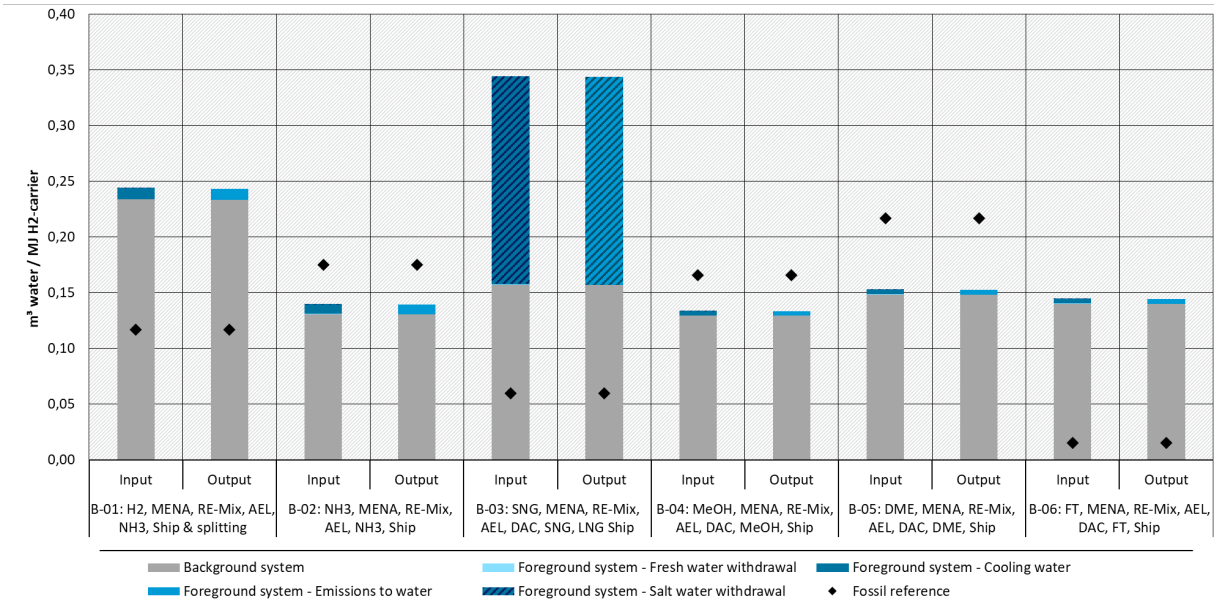
Water demand is made up of various contributions. It is also divided into water intake and water discharge. On the intake side, the following variables are distinguished for the foreground system: fresh water withdrawal, cooling water and salt water withdrawal. These variables have been summarised for the background system. On the discharge side, all liquid and gaseous water flows leaving the system have been summarised. Figure 45 shows the results for the base paths of the PtGLS products:

It is clear to see that water requirements in the background system are significantly higher than in the foreground system. The requirements in the background arise mainly from the construction of power generation plants and infrastructure. Cooling water requirements play a prominent role in the requirements of the foreground system. The freshwater demand for electrolysis, on the other hand, is significantly lower. Since the cooling water used also leaves the system again, the water balance is closed at this point. Freshwater is converted into hydrogen by electrolysis and cannot leave the system as water on the output side. The increased contributions to the provision of SNG in the base case B-03 (hatched bars) result from LNG transport. Regasification requires heat, which is extracted from the surrounding seawater in a flow heat exchanger.

Nevertheless, it should not be assumed that the water requirements of an electrolysis plant are negligible. An electrolyser with a capacity of 500 MW requires approximately 0.8 million m^3 of fresh water and, depending on the cooling system, up to 8 million m^3 of cooling water per year for approximately 8,000 operating hours. By way of comparison, BASF's water requirements at

its Ludwigshafen site amount to around 18 million m^3 of process water (from groundwater) and around 900 million m^3 of cooling water (from the river Rhine) per year.

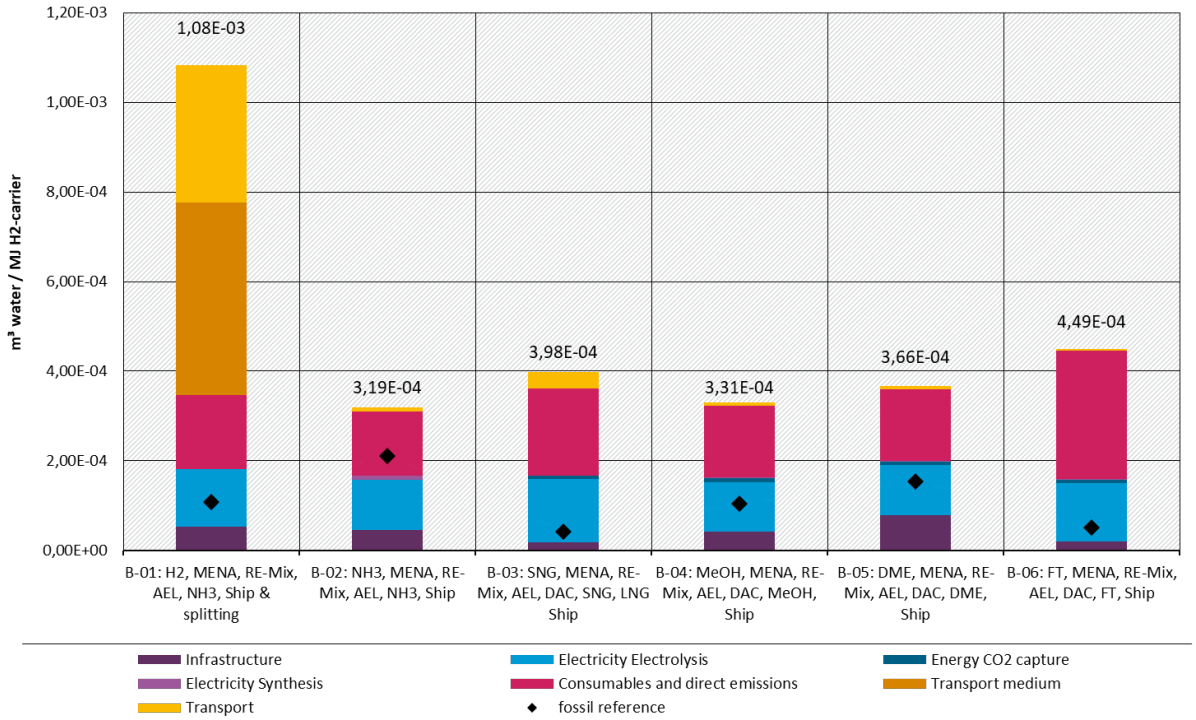
Figure 45: Water consumption and release in the provision of PtGLS products in the base case.



Source: own representation, ifeu.

Figure 46 shows the results for **freshwater demand on the consumption side** due to the provision of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. For base case B-01, the categories "**transport**" and "**transport medium**" account for almost 70% of the result. This is mainly due to the fossil fuel content of the grid electricity used. For all base cases, the categories "**Consumables and direct emissions**" contribute significantly due to the water requirements of electrolysis, and the category "**Electricity electrolysis**" contributes significantly due to the manufacture of power generation plants.

Figure 46: Freshwater consumption for the provision of PtGLS products in the base case



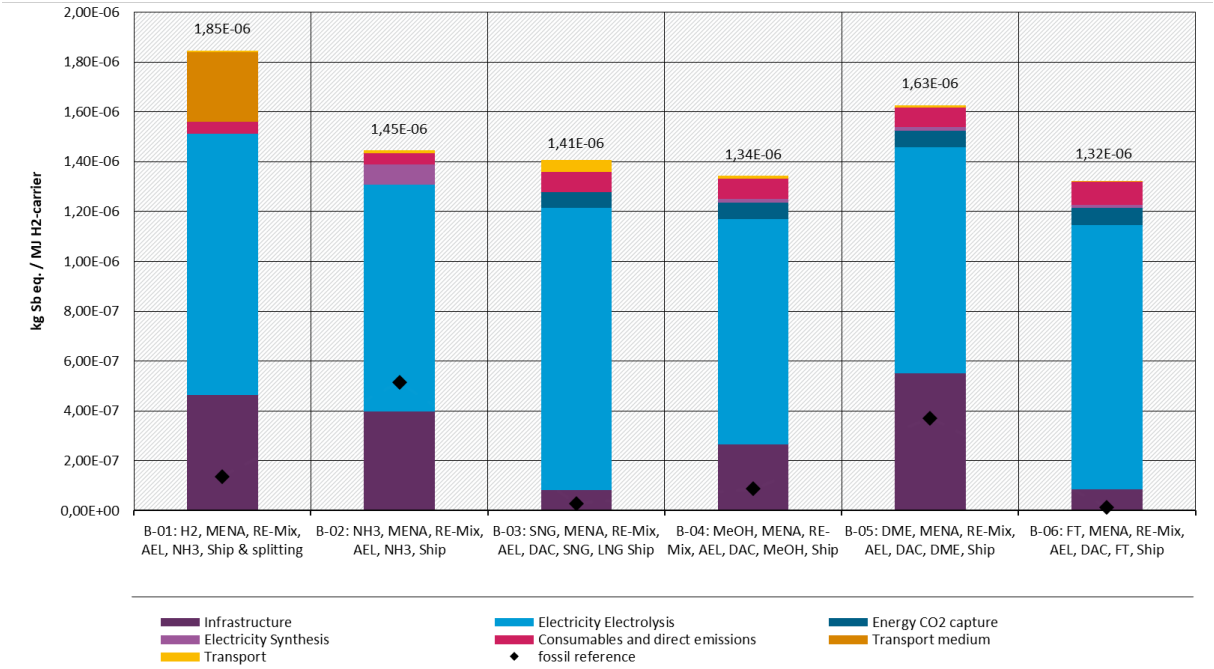
Source: own representation, ifeu.

4.3.2.9 Resource consumption ($ADP_{elements}$)

Figure 47 shows the results for the abiotic resource depletion potential ($ADP_{elements}$) for minerals and metals used in the production of the PtGLS products considered in the base cases, each based on 1 MJ of calorific value. The results of all base cases are close to each other. The largest contribution in each case is made by the category **"electricity electrolysis"**. In case B-01, around 15% of the abiotic resource depletion potential for minerals and metals is generated by the grid electricity used for the synthesis and splitting of the **transport medium** ammonia. The construction of the synthesis plants leads to a significant contribution from the **"infrastructure"** category.

All base cases also show a significant increase in abiotic resource depletion potential compared to the respective fossil reference. For case B-01 (H_2 via NH_3), this potential is around 13 times higher than the reference, and for case B-02 (NH_3), it is around three times higher. The provision of synthetic natural gas (B-03) depletes resources around 50 times more than fossil fuels. For DME (B-05), the result is around four times that of the reference, for methanol (B-04) around 15 times and for FT fuels (B-06) around 90 times.

Figure 47: Abiotic resource depletion potential for minerals and metals in the provision of PtGLS products in the base case



Source: own representation, ifeu.

4.4 Summary and discussion of the results

In a summary classification of the life cycle assessment calculations, this section identifies the factors that significantly influence the environmental impacts of the provision of synthetic energy sources based on renewable energies. In addition, possible conflicts of interest for paths and path groups are identified – for example, when particularly low greenhouse gas emissions are accompanied by high values in other impact categories.

A key question is first of all what **climate impacts** synthetic energy sources have and whether they provide relief compared to fossil reference products:

- For **ammonia, methanol, DME and Fischer-Tropsch fuels**, a **reduction in climate impact of around 80%** can be achieved in the base cases considered. For **synthetic natural gas, a reduction of 60% is** possible. For **hydrogen,** which is shipped bound in the transport medium ammonia, the climate impact can **be reduced** by around **50%** – if renewable electricity is also used to produce the transport medium.
- The use of **grid electricity**, which usually also contains a significant proportion from non-renewable sources, **worsens the climate balance** in all process steps. This applies above all to its use in electrolysis, but also in the synthesis, liquefaction or splitting of the transport medium and in the power supply of pipeline compressors.
- Since renewable electricity accounts for 40 to 60% of the climate impact in most base cases, the **choice of renewable electricity source** has a noticeable influence on the overall result. **Wind power** is the source with the **lowest climate impact** and, at the same time, shows only small absolute differences per kWh between different locations. The results for electricity from **photovoltaics** show **greater differences between locations,** but even in the most favourable case, they are **two to three times higher than those for wind power.**

- Of the **hydrogen transport options** examined, import via **pipeline** has **the lowest climate impact**. Transport using **LOHC and DME** as transport media is **significantly higher.** If **ammonia** is used as the transport medium, this can compete with the results of **pipeline transport**, but only if **renewable electricity** is used **for NH_3 synthesis**. Otherwise, the climate impact is twice as high as that of pipeline transport.
- **Importing "blue" and "turquoise" hydrogen** using ammonia as a transport medium has a climate impact that **is hardly better than, or even worse than, the fossil fuel reference.** The main reasons are greenhouse gas emissions in natural gas supply (especially methane) and CO_2 emissions in reforming. The production of "turquoise" hydrogen using the technology examined here leads to worse results than those for "blue" hydrogen.
- The **production of "blue" hydrogen in Germany**, on the other hand, could **reduce** the climate impact by **40–70%** compared to conventional production (reference). The prerequisite for the largest possible reduction is the **import of natural gas with low carbon footprint** and the use of the process with **the highest possible CO_2 capture rate**. The volume required for storage (CCS) is not included.
- The choice between the AEL and PEMEL **electrolysis technologies** examined makes **little difference.**
- There are **no major differences** between the production of renewable **ammonia** in **the countries** examined and in **Germany**, as the advantages of electricity generation are almost offset by the disadvantages of transport.
- **Transport** plays a significant role for **synthetic methane**. As with hydrogen, transport by **pipeline** is **the option with the lowest impact** for distances of up to 3,000-4,000 km. Liquefied **transport by ship** is **more advantageous** for **longer distances**, but generally negates the advantages of higher renewable energy full-load hours in distant countries.
- For the liquid energy carriers **methanol, DME and Fischer-Tropsch fuel**, the **climate impact of the renewable electricity used** plays a greater role because the demand for hydrogen is high. Compared to gaseous energy carriers, **transport by ship** contributes **less**.
- The climate impact of producing petrol via the methanol-to-gasoline route is around **a quarter higher than that of the Fischer-Tropsch route**, but still **70% lower than the fossil fuel reference**.

In contrast to the carbon footprint, most supply pathways show **a significantly higher environmental impact** in all **other impact categories** compared to the respective fossil fuel reference.

- In the "acidification" category, pathways that use **ammonia** perform **particularly poorly**. However, the provision of **synthetic natural gas** and the liquid energy sources **methanol, DME and Fischer-Tropsch fuels** also perform significantly **worse than the fossil reference**. This is mainly due to emissions of sulphur dioxide, nitrogen oxides and ammonia in background processes (infrastructure and transport).
- The provision of synthetic energy sources is also **often as eutrophicating (overfertilising) as their fossil fuel counterparts**. Eutrophication is also largely caused by emissions of ammonia and nitrogen oxides, but phosphate emissions into water are also added to this – the latter when fossil fuel-based grid electricity is used for transport processes.

- In terms of their **ozone depletion potential**, only **methanol and DME** are **slightly better** than the fossil reference. The base cases for hydrogen and ammonia are above this. **Fischer-Tropsch fuels are many times more harmful to the ozone layer** than fossil diesel. The reason for this is the manufacture of electrolysers, in which tetrafluoroethylene is used in the production of the membrane.
- The potential for **summer smog** formation is significantly **lower** for **ammonia, methanol, DME and Fischer-Tropsch fuels than for the respective fossil fuel reference**. However, the provision of **synthetic natural gas and hydrogen** via the transport medium ammonia is **many times worse**. In all cases, this is due to nitrogen oxide emissions in background processes (transport, infrastructure).
- **Particulate matter emissions** are potentially **all significantly higher than those of the respective fossil fuel reference.** For all synthetic products, nitrogen oxide emissions from infrastructure and transport processes contribute significantly. If grid electricity is used, SO_2 emissions are added. Supply paths involving ammonia lead to high particulate matter potential due to NH_3 emissions.
- The **cumulative energy consumption** for almost all synthetic products is **equal to or higher than that of the respective fossil fuel reference**. Only **ammonia and methanol require slightly less energy input** in this comparison. In all cases, the electricity input into the electrolysis process is decisive.
- **The land required** for renewable electricity generation is the reason why the **hemeroby-weighted land use** of synthetic products is **around 20-30 times higher** than that of fossil reference products.
- **Water demand** arises primarily in the background system, in particular from **fossil fuel power plants and infrastructure**. In the foreground system, **the cooling water demand for electrolysis dominates**, while the **fresh water demand for electrolysis** is **low** in comparison. Nevertheless, the latter should not be neglected, as the cooling water leaves the plant again, while the water for electrolysis is permanently extracted from the local system.
- All base cases also show a **significant increase** in the **abiotic resource depletion potential for minerals and metals** in relation to the respective fossil reference. The reason for this is the demand for the construction of power generation and synthesis plants.

5 Technical measures to determine and limit climate and environmental effects

The previous sections clearly show that the manufacture and transport of PtGLS products have an impact on the environment. The provision of products was modelled there as it already takes place today or is expected to take place initially. However, it is desirable to minimise the environmental impact by optimising the supply chains. This section deals with this objective. Section 5.1 first identifies the processes that contribute most to the environmental impacts identified. Section 5.2 presents options for reducing these environmental impacts, and section 5.3 derives and calculates future improvements based on the supply paths defined in section 3, implementing the options identified in section 5.2. This allows the corresponding mitigation effects to be quantified and possible impacts on other impact categories to be described. Section 5.4 presents the uncertainties underlying the calculations, and section 5.5 provides a summary overview of the most important mitigation measures.

5.1 Relevant environmental impacts of the provision of PtGLS products

The results of the life cycle assessment (see section 4.3) clearly show that the provision of PtGLS products has significant environmental impacts in all impact categories examined.

The most significant contributions to the individual environmental impacts are caused by the following processes:

- **The synthesis and splitting of the transport medium**, in particular ammonia, but also the loading/unloading of LOHC or DME, contribute significantly to all environmental categories.
- The construction and operation of **renewable power generation plants** contribute significantly to all environmental categories, in particular land and resource requirements.
- If **fossil fuels or** grid electricity are used for transport or other processes, significant emission-related environmental impacts occur.
- The production of the **infrastructure** and the **production facilities** contribute in particular to ozone depletion and resource requirements.
- **The extraction and transport of natural gas** for blue/turquoise hydrogen have a significant impact on the climate and contribute greatly to ozone depletion due to the methane losses that occur in the process, as well as making significant contributions in other impact categories.
- Direct **emissions** from production facilities are primarily uncaptured CO_2 from the production of blue and turquoise hydrogen, which contribute to the climate impact. However, NH_3 from ammonia synthesis is also a relevant pollutant.
- **The use of water** as a raw material and coolant for electrolysis and synthesis leads to water stress depending on the location.

Appropriate measures to reduce the environmental impact compared to the current status quo of the technologies used should therefore be implemented as a priority in these process steps.

5.2 Options for reducing environmental impacts

Based on the analysis of the relevant environmental impacts in section 5.1, there are several options for reducing environmental impacts. These include measures for resource efficiency, i.e. the use of technologies that require fewer raw materials, the use of materials with lower environmental impacts, the reduction of energy consumption and the reduction of direct emissions.

The implementation of measures is also classified according to time frame. Short-term implementation can be carried out almost immediately using existing technologies. Medium-term implementation means adapting technologies or converting plants within a few years. Long-term measures require longer development phases or are based, for example, on major changes to value chains, which cannot be implemented without further ado.

The following specific measures to reduce environmental impacts along the PtGLS value chains are proposed:

- **Ship transport will use PtGLS products as fuel**: In future, it is expected that international freight transport will be able to use the corresponding PtGLS products as fuels. An NH_3 tanker will then use NH_3 as fuel, a classic tanker will run on FT fuels, etc. The switch to PtGLS fuels will avoid the use of fossil heavy fuel oil and defossilise transport. Fischer-Tropsch diesel produced from renewable electricity sources is assumed to be used for the transport of hydrogen with LOHC as a carrier. Time frame for implementation: long term; dependent on the widespread availability of PtGLS products.

- **LNG liquefaction will be electrified**: in order to conserve valuable PtGLS products (and renewable electricity), the energy required to operate liquefaction plants will not be supplied by SNG in turbines, but by electricity in electrically powered compressors. This will reduce CO_2 and methane emissions. Time frame for implementation: short to medium term; electrification can take place immediately, supply with renewable electricity depends on the expansion of renewable electricity supply in the country of delivery.

- **PtL products are distributed in Germany using electric trucks**: In the future, it is expected that most heavy goods vehicles in Germany will be electric trucks. They will be powered by renewable electricity. Time frame for implementation: medium term; electrification of trucks is ramping up, supply of renewable electricity depends on the expansion of renewable energy supply and fast charging points in Germany.

- **Power supply** for all processes (ATR/SMR, NH_3 synthesis, NH_3 and LOHC splitting, gas pipeline transport, loading/unloading, etc.) **is provided from renewable energy sources**. This means that no more grid power is drawn in the foreground system, thus ensuring a completely renewable energy supply for the PtGLS value chain. The energy transition is a basic prerequisite for the use of renewable electricity from the general electricity grid and the resulting reduction in environmental impact. Time frame for implementation: long term; dependent on the expansion of the renewable electricity supply and opportunities for the electrification of high-temperature processes.

- **NH_3 and NO_X emissions in NH_3 synthesis and NH_3 cracking** must be avoided as far as possible by selective catalytic reduction (SCR) or non-selective non-catalytic reduction. The German legal regulation TA-Luft[10] specifies emission limits of 100-300 mg NO_X/m^3 exhaust

[10] Technical Instructions on Air Quality Control, translated version: https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Luft/taluft_engl.pdf

air for ammonia production plants (number 5.4.4.1.12a). At European level, the guidance documents on best available techniques state that values of less than 100 mg NO_X/m^3 exhaust air can be achieved in newly approved ammonia plants (European Commission 2007). For NH_3 emissions, only ammonia slip from SCR plants is currently addressed, with a limit value of 10 mg NH_3 /m^3 exhaust air (§ 27 of the 13th BImSchV, German Federal Immission Control Act). There are currently no state-of-the-art specifications for ammonia splitting. For a pilot plant, the 44th BImSchV (German Federal Immission Control Act) was used with limit values of 200 mg NO_X/m^3 exhaust air and 30 mg NH_3 /m^3 exhaust air when using residual gases (NH_3, H_2, ...) as fuel gas. According to industry representatives, it is already technically feasible to reduce emissions to close to the detection limit.

- There is currently a lack of reliable data for the precise quantification of **ammonia emissions during maritime transport**. However, it is known that boil-off gases, leaks and combustion products in the engine are potential sources of emissions. Strict safety measures and further research are necessary to minimise the risks. Compared to the loss of 0.025% per day assumed in the base cases (de Kleijne et al. 2024), a reduction of at least 95% should be implemented. Time frame for implementation: short to medium term; exhaust gas purification can be taken into account immediately in existing and new plants. Development work is necessary for marine engines.

- Use of **seawater desalination** for electrolysis: In order to reduce freshwater requirements (for details on water availability and possible limits, see section 4.2), process water is provided from seawater desalination. The electricity required for desalination is obtained from the relevant regional renewable energy sources. However, the environmental impact of large-scale seawater desalination can be considerable. In particular, the following effects may occur:

- Discharging the highly concentrated brine back into the sea leads to a local increase in salinity and a decrease in the brine at the sea floor. This leads to local oxygen depletion and the alteration of benthic habitats. Studies show significant changes in fish diversity within 55 metres and invertebrate diversity within 125 metres of the discharge points (Kelaher et al. 2022).

  - Intake of seawater in which marine organisms live (Abouzied 2023).
  - Antifouling and disinfectants from the pre-treatment of seawater can be toxic to marine organisms (Abouzied 2023).
  - Heat input into the sea and resulting local temperature increase

  Time frame for implementation: medium term; seawater desalination plants must be planned and built as needed and supplied with renewable electricity.

- **Polytetrafluoroethylene (PTFE) and other per- and polyfluoroalkyl substances (PFAS) are replaced by polysulfones**: In AEL and PEMEL electrolysis, membranes based on fluorinated polymers are replaced by polysulfone-based membranes. Time frame for implementation: medium term; alternative membranes are being researched but have not yet been implemented on an industrial scale.

- The **separation efficiency of CCS plants** in the natural gas reforming process is increased from 90% to 98%, which requires an increase in the power consumption of the amine scrubbing process of around 35% (Antonini et al. 2020). This means that only a small proportion of the fossil CO_2 from reforming enters the atmosphere (93% capture rate for the

entire system). Time frame for implementation: short term; during engineering of CCS plants they can be designed for a higher capture rate .
For CO_2 storage, the permanent integrity of the storage sites must be guaranteed. This requires suitable technical measures for measuring storage levels, feed-in and withdrawal quantities, as well as monitoring approaches for possible leaks, their localisation and elimination. Time frame for implementation: long term, as there is little experience in these areas to date.

- **Process heat is provided from renewable electricity**: The generation of process heat in the chemical industry is currently based largely on the combustion of natural gas. The aim must be to electrify these processes, in particular for the splitting of LOHC to recover hydrogen. Time frame for implementation: medium term; conversion of existing processes is being tested industrially in some cases, and new plants can already be planned on this basis.
- **Natural gas** as a raw material for the production of blue hydrogen is extracted and transported under **minimisation of methane losses**. Currently, natural gas extraction in Norway in particular meets these criteria. Although Norway covered 48% of Germany's gas supply[11] and 27% of the EU's gas supply in 2024, its natural gas production only accounts for about 3% of global natural gas production (Energy Institute 2024), and Norway's reserves account for approximately 1% of global natural gas reserves. This source is therefore limited. In order to be able to use natural gas from other production areas for the production of blue hydrogen with a low contribution to the greenhouse effect, methane losses must also be minimised there. This can be achieved primarily by
  - avoiding leaks through regular monitoring and repair (LDAR campaigns)
  - new extraction techniques that recover methane instead of releasing it into the atmosphere, thereby avoiding flaring
  - optimising pressure control and compressors to reduce methane losses

  Time frame for implementation: short term; the measures can be implemented in the extraction areas.
- **Heat integration of DAC plants with PtGLS plants** at the relevant location. The combustion of natural gas for heat supply can be partially or completely avoided by coupling processes to such an extent that waste heat from one process is used in another. GHG emissions from natural gas combustion can thus be avoided and energy efficiency increased at the same time. Time frame for implementation: short to medium term; can be taken into account directly in planning.
- The use of **water-saving cooling systems** for electrolysis plants. In the base cases, cooling water consumption of 40 litres per kg of hydrogen is estimated in open circuit cooling systems. Various options could be implemented to minimise fresh water requirements. As it is difficult to assess which measures are technically feasible and sensible at which locations, these are discussed briefly here:
  - Air-dry cooling systems can reduce water consumption by 95% (Saravia et al. 2024), but they require more energy to circulate air as a cooling medium. The additional cooling capacity is specified in the Reference Document for industrial cooling systems (European Commission 2001) as 26–38 kW_{el} /MW_{th} compared to open flow cooling systems.

[11] https://www.bundesnetzagentur.de/DE/Gasversorgung/a_Gasversorgung_2024/start.html

Converted to the production of 1 kg of hydrogen in electrolysis, this would mean up to 0.38 kWh/kg H_2 of additional electricity consumption. It remains questionable whether air cooling systems can provide sufficient heat transfer and be technically implemented in regions with very warm and dry air.

- In coastal locations, cooling with seawater in two cooling circuits is therefore also conceivable. An open system through which seawater is passed and a closed system that transfers heat from the electrolysis to the seawater. Problems such as corrosion and fouling of plant components may arise. Corrosion-resistant steel could be used to combat corrosion, but this would increase investment costs. It is unclear which anti-fouling agents would be used and how their emissions would affect marine ecosystems. In addition, it should be examined how much heat would be absorbed into the seawater with such a cooling system and what ecological effects would be associated with warming.
- Another approach would be to supply the cooling system via seawater desalination. This would reduce the demand for fresh water, and the electricity required for desalination is lower than that required for dry cooling. To supply 40 litres of cooling water, the additional electricity requirement for desalination would be approximately 0.002 kWh/kg H_2. Increased emissions of the concentrated permeate solution back into the marine ecosystem are likely to pose the greatest risk of negative environmental effects. Time frame for implementation: short term; can be taken into account in the planning of electrolysis plants.

- When **selecting refrigerants** for process cooling systems, halogenated hydrocarbons are avoided in order to reduce the risk of ozone-depleting emissions. In addition, only refrigerants with low GHG potential are used, such as propane (R-290), isobutane (R-600a), ethane (R-170), ammonia (NH_3, R-717) or carbon dioxide (CO_2, R-744). Time frame for implementation: short term; can be taken into account in the planning of PtGLS plants.
- **Saving surface area:** The generation of renewable electricity in particular requires a large amount of surface area. The measures to limit the amount of land required are minimal, apart from increasing the efficiency of electricity generation per unit of land. However, if the degree to which the land is removed from nature (hemeroby) is included as an assessment criterion (Fehrenbach et al. 2015, 2019), the following criteria must apply to the land used:
  - **Where possible, multiple use of already sealed or partially sealed areas, e.**g. photovoltaics on roof surfaces or car parks
  - **Partial use of agriculturally usable land is possible; co-use, such as agri-photovoltaics, should be sought**
  - **Prohibition of the use of unmanaged forests, wetlands and grassland**

  Time frame for implementation: medium term; dependent on the framework conditions for the construction of new photovoltaic systems.

5.3 Quantification of mitigation effects

To quantify the mitigation effects of the measures presented in section 5.2, target scenarios were defined based on the baseline scenarios described in section 3 and some of the variations. When defining the target scenarios, all of the measures presented in section 5.2 were assumed to have been implemented, with the following restrictions:

- The use of water-saving cooling systems for electrolysis plants was not implemented because the location of the plants could not be defined precisely enough.
- Since no coolants are used in the foreground processes considered in the model, no adjustments were made to the model.
- Land use occurs primarily in electricity generation. This was not adjusted in the model.

5.3.1 Description of target scenarios

The target scenarios are derived by combining the applicable individual measures in the corresponding base scenarios or variants. Similarly, the path designations are composed of the respective process steps.

An example of the target scenario "Z-01: H_2, MENA, RE mix, AEL, NH_3, ship & splitting":

- The target product hydrogen is produced in the MENA region using renewable electricity by means of AEL, which uses polysulphone membranes;
- Water for AEL is obtained through seawater desalination, reducing the demand for fresh water;
- Ammonia is the transport derivative and is also produced using renewable electricity – emissions of NH_3 and NO_X are avoided;
- Ammonia is transported to Germany by ship with an NH_3 engine and split into H_2 there with the aid of renewable electricity;
- H_2 is fed into the H_2 gas distribution network; the compressors are also powered by renewable electricity.

Twelve paths were included in the consideration of target scenarios. The following list summarises the individual measures applied:

- Z-01: H_2, MENA, RE mix, AEL, NH_3, ships & splitting
  AEL with polysulphone membranes, seawater desalination, transport medium NH_3 with RE electricity, emission reduction NH_3 synthesis, ship with NH_3 engine, NH_3 splitting with RE electricity, emission reduction NH_3 splitting, H_2 gas distribution network with RE electricity
- Z-02: NH_3, MENA, renewable energy mix, AEL, NH_3, ship
  AEL with polysulphone membranes, seawater desalination, emission reduction NH_3 synthesis, ship with NH_3 engine, transport in Germany with electric trucks
- Z-03: SNG, MENA, renewable energy mix, AEL, DAC, SNG, LNG ship
  AEL with polysulphone membranes, seawater desalination, SNG liquefaction with renewable electricity, SNG marine fuel
- Z-04: MeOH, MENA, RE mix, AEL, DAC, MeOH, ship
  AEL with polysulphone membranes, seawater desalination, ship with MeOH engine, transport in Germany with electric trucks
- Z-05: DME, MENA, RE mix, AEL, DAC, DME, ship
  AEL with polysulphone membranes, seawater desalination, ship with DME engine, transport in Germany with electric trucks

- Z-06: FT, MENA, RE mix, AEL, DAC, FT, ship
  AEL with polysulphone membranes, seawater desalination, ship with FT fuel, transport in Germany with electric trucks
- Z-09: H_2, DE, RE mix, AEL, GH_2, pipeline
  AEL with polysulphone membranes, seawater desalination, H_2 gas distribution network with RE electricity
- Z-10: H_2, MENA, RE mix, AEL, GH_2, pipeline
  AEL with polysulphone membranes, seawater desalination, H_2 gas pipeline with renewable electricity, H_2 gas distribution network with renewable electricity
- Z-12: H_2, MENA, renewable energy mix, AEL, LOHC, ship & splitting
  AEL with polysulphone membranes, seawater desalination, LOHC transport medium with RE electricity, LOHC splitting with RE electricity, H_2 gas distribution network with RE electricity, ship with FT fuel from Z-06...
- Z-26: SNG, AU, RE mix, AEL, DAC, SNG, LNG ship
  AEL with polysulphone membranes, seawater desalination, SNG liquefaction with renewable electricity, SNG marine fuel
- Z-28: MeOH, AU, renewable energy mix, AEL, DAC, MeOH, ship
  AEL with polysulphone membranes, seawater desalination, ship with MeOH engine, transport in Germany with electric trucks
- Z-47: H_2, DE, RE mix, ATR + CCS, NG from NO
  Natural gas upstream chain with minimal methane leakage, CO_2 capture rate 98%, RE auxiliary power reforming, H_2 gas distribution network with RE electricity

5.3.2 Comparison of the environmental effects of base cases, variants and target scenarios

5.3.2.1 Climate change

Figure 48 shows the results of the target scenarios in comparison to the corresponding base cases and variants. For all target scenarios, these are below the reference cases.

This reduction is particularly pronounced for the **supply of hydrogen.** In the case of transport using ammonia as a transport medium (B-01 and Z-01), the climate impact is reduced by 72%. The main reason for this is the production and splitting of ammonia using renewable electricity. As with all target scenarios involving AEL, a slightly counteracting effect arises from the electricity demand for seawater desalination. This is based on the assumption that ammonia causes only very low emissions when used as a marine fuel. Given the current state of technology, this cannot be considered a certainty for the future.

In the case of production in Germany (V-09 and Z-09), the impact is reduced by 27%. The main reason here is also the use of renewable electricity for distribution via gas pipelines.

For the transport of hydrogen using LOHC as the transport medium (V-10 and Z-10), the climate impact is reduced by 72%. This is due to the use of renewable electricity in LOHC synthesis and, above all, the use of renewable electricity as a heat source instead of heat from natural gas in LOHC splitting. Shipping with FT fuel also contributes to the reduction in impacts, as does the transport of hydrogen via gas pipeline, with compressor operation based on renewable electricity.

Transport via gas pipeline from the MENA region (V-12 and Z-12) also benefits from the use of renewable electricity. Due to the long distance involved, the reduction here is 58%.

In the target scenario for "blue" hydrogen, which envisages importing natural gas from Norway and subsequent reforming with CCS (Z-47), emissions are reduced by 49% compared to the V-47 variant. The main reasons for this are that the electricity for reforming is obtained from renewable energy sources using the ATR process and the CO_2 capture efficiency is very high at 98%. Overall, scenarios V-47 and Z-47 use autothermal reforming (ATR), currently the best and most efficient technology for low-GHG hydrogen production. This is combined with the lowest-emission supply of natural gas. Norway's current production potential is limited and is set to decline further in the future due to dwindling natural gas fields. In addition, both scenarios assume permanent storage of CO_2 in underground reservoirs. These are very optimistic conditions.

Compared to the fossil reference (95 g CO_2 eq. / MJ H_2), the target scenarios offer reduction potentials for the contribution to climate change in the range of 66–85%. The conversion of hydrogen to ammonia results in higher emissions (32 g CO_2 eq. / MJ H_2), as more hydrogen has to be produced overall, losses occur during reconversion and N_2O is a relevant emission during transport. Even in the best-case scenario, only a 66% reduction compared to the fossil fuel reference can be achieved in this supply chain. All target scenarios that do not involve conversion to NH_3 have lower emissions of 14–18 g CO_2 eq. /MJ H_2.

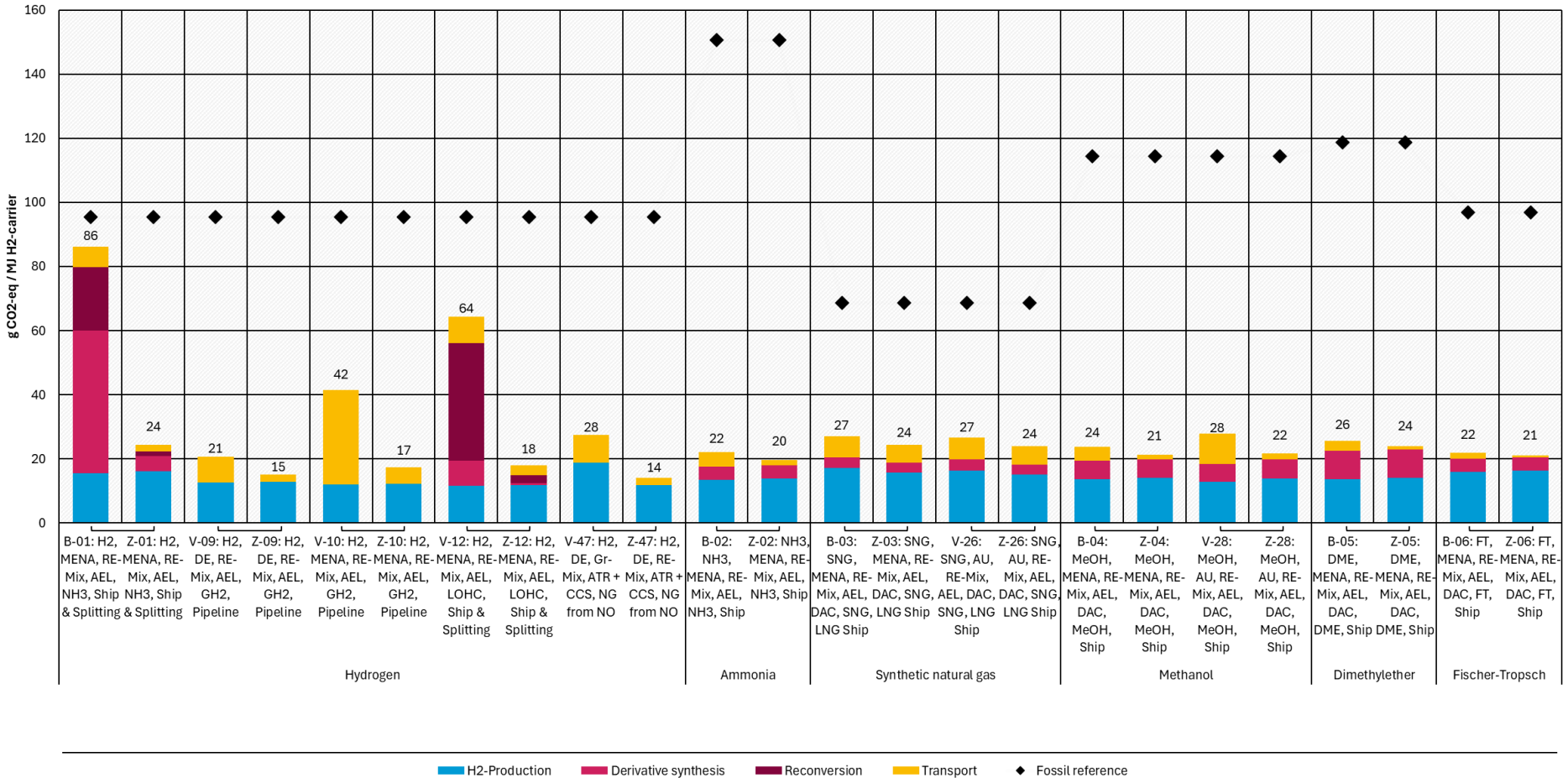
For the provision of **other PtGLS products**, there are only minor changes in the target scenarios, as the use of renewable electricity in all relevant process steps has already been taken into account in the base cases and their variants. Therefore, the most relevant factor is transport emissions, which are reduced by the use of PtGLS products as fuels in shipping. For the product ammonia (Z-02), there are improvements of 11% compared to the base case.

Synthetic natural gas (Z-03 and Z-26) and methanol (Z-04) achieve savings of 10%. If methanol is imported from Australia (Z-28), the greatest reduction potential for PtGLS is 22% compared to the baseline scenario, but this is also based on a higher starting level.

In contrast, the products DME (Z-05) and Fischer-Tropsch fuels (Z-06) only achieve emission reductions of 4–6% compared to the base cases in the target scenarios.

Overall, the implementation of reduction measures can have a major impact on reducing GHG emissions, particularly in the production of hydrogen. In optimal cases, values of 15–20 g CO_2 eq. /MJ H_2 and 20–24 g CO_2 eq./MJ for other PtGLS products can be achieved. The energy transition is a basic prerequisite for supplying all processes along the supply chain with renewable electricity.

Figure 48: Climate change category – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.2 Acidification

Air emissions of nitrogen oxides (NO_X), sulphur dioxide (SO_2) and ammonia (NH_3) contribute in particular to the acidification category. Figure 49 shows the results of the target scenarios in the acidification category compared to the corresponding base cases and variants.

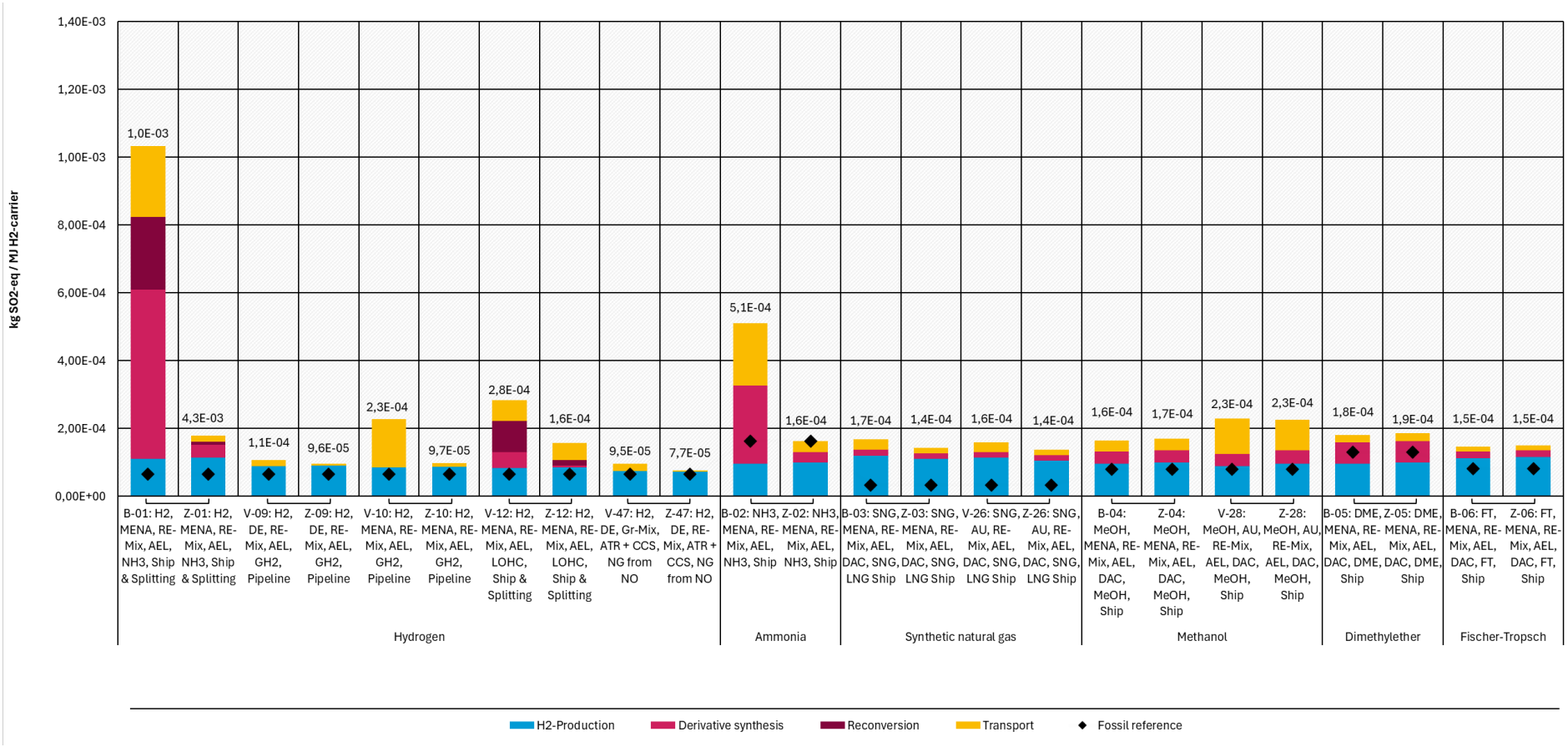
In the **hydrogen** cases, the use of renewable electricity and exhaust gas purification for the synthesis and splitting of NH_3 as a transport medium (Z-01), the operation of pipelines (Z-09, Z-47), and LOHC production and reconversion (Z-12) result in a reduction in acidification potential. However, in most cases, the values are still 20–50% above the fossil reference. NH_3 and LOHC as hydrogen carriers are exceptions. Ammonia emissions from NH_3 synthesis continue to contribute to acidification. For LOHC, the need for catalysts and electricity for loading and reconversion, as well as the low density during transport, lead to increased values (140% above the fossil reference).

The acidification potential of the provision of **ammonia** (B-02 and Z-02) is reduced by approximately 70% through the use of renewable electricity and exhaust gas purification, reaching the value of the fossil fuel reference.

The provision of **SNG** results in reductions in acidification potential of approximately 15%, in particular through the use of renewable electricity for liquefaction instead of SNG-powered turbines, which means that less SNG needs to be produced.

All **other PtGLS products** result in very slight increases in acidification potential, which are composed of SO_2 emissions from seawater desalination and the additional hydrogen required to produce the fuel.

Figure 49: Acidification category – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.3 Eutrophication

The eutrophication category includes, in particular, air emissions of nitrogen oxides (NO_X), nitrogen dioxide (N_2O) and ammonia (NH_3), as well as emissions of nitrogen and phosphate compounds (NH_4^+, NO_3^-, PO_4^-) to water.

Figure 50 shows the results of the target scenarios in the eutrophication category compared to the corresponding base cases and variants.

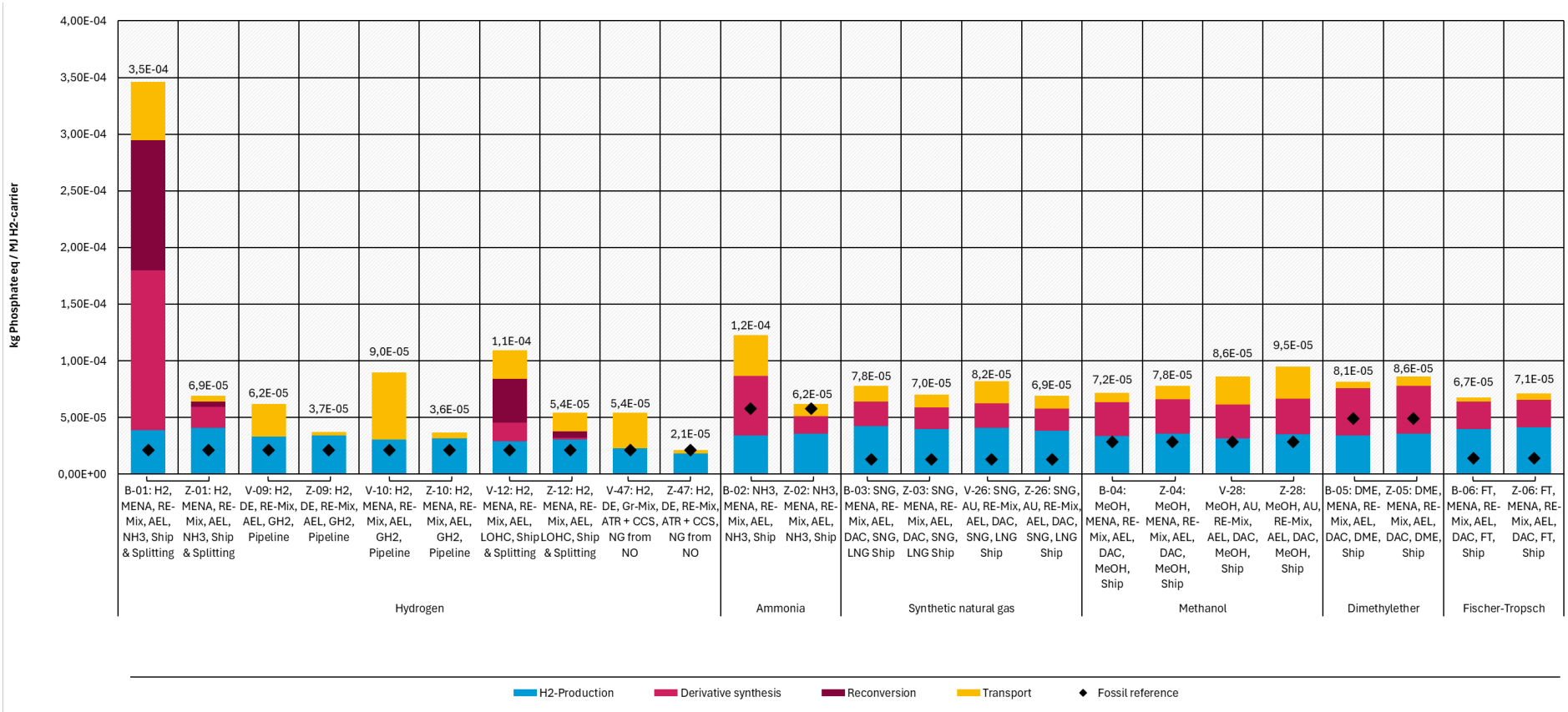
In the **hydrogen** cases, the use of renewable electricity and exhaust gas purification for the synthesis and splitting of NH_3 as a transport medium (Z-01), the operation of pipelines (Z-09, Z-47), and LOHC production and reconversion (Z-12) results in a reduction in eutrophication potential, so that in most cases values are achieved that are approximately 70% above the fossil reference. NH_3 and LOHC as hydrogen carriers are exceptions. Ammonia emissions from NH_3 synthesis continue to contribute to eutrophication. For LOHC, the need for catalysts and electricity for loading and reconversion, as well as its low density during transport, lead to increased values (150% above the fossil reference). Blue hydrogen production in Germany (Z-47) achieves the fossil reference value.

The eutrophication potential of the provision of **ammonia** (B-02 and Z-02) is reduced by approximately 50% through the use of renewable electricity and exhaust gas purification, reaching the value of the fossil fuel reference.

The provision of **SNG** results in reductions in eutrophication potential of approximately 10–15%, in particular through the use of renewable electricity for liquefaction instead of SNG-powered turbines, which means that less SNG needs to be produced.

All **other PtGLS products** result in increases in eutrophication potential of 5–10%, which is composed of the additional hydrogen required to produce the fuel and a contribution from the production of the electric truck.

Figure 50: Category eutrophication – comparison of base cases, variants and target scenarios for selected paths.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.4 Ozone depletion

Air emissions of halogenated hydrocarbons contribute in particular to the ozone depletion category. Figure 51 shows the results of the target scenarios in the ozone depletion category compared to the corresponding base cases and variants.

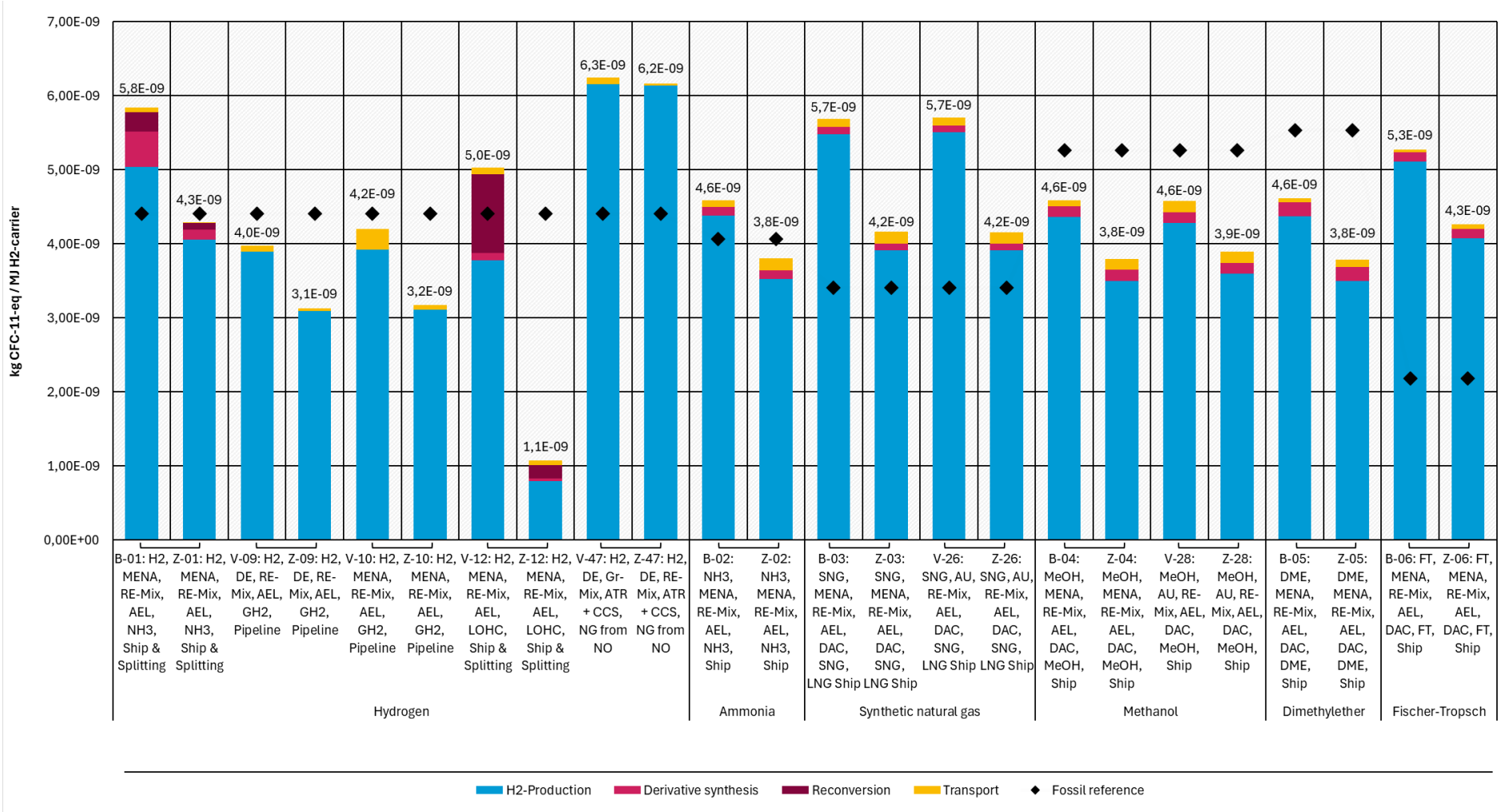
In the **hydrogen** cases, except for the production of blue hydrogen (V-47 and Z-47), replacing the PTFE membrane with a polysulfone membrane reduces the contribution of hydrogen production to ozone depletion by approximately 20%. This measure makes the largest reduction contribution. The use of renewable electricity for the synthesis and reconversion of ammonia and LOHC reduces the contribution of these sub-steps by approximately 70–80% (Z-01 and Z-12). The use of renewable electricity to operate pipelines and gas distribution networks leads to a reduction in ozone depletion potential in the transport sector of approximately 70%. However, the contribution of transport to the overall result was already low in the initial situations. The measures enable all scenarios for the provision of "green" hydrogen to fall below the fossil reference values.

In the case of "blue" hydrogen supply, the measures result in virtually no changes, as the most important measure, the replacement of the membrane, is irrelevant in this process path.

The ozone depletion potential of the provision of **ammonia** (B-02 and Z-02) is reduced by approximately 20% by replacing the membrane, as in the hydrogen cases. Since the base scenario B-02 already assumes that ammonia synthesis is powered by renewable electricity, there are no additional effects in derivative synthesis.

All **other PtGLS products** result in a reduction in ozone depletion potential of approximately 20–30%, primarily through the replacement of the membrane and also through the use of renewable electricity in synthesis and transport.

Figure 51: Ozone depletion category – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.5 Summer smog

Air emissions of nitrogen oxides (NO_X), sulphur dioxide (SO_2) and volatile hydrocarbons (NMVOC) contribute in particular to the summer smog category. Figure 52 shows the results of the target scenarios in the summer smog category compared to the corresponding base cases and variants.

The particulate matter formation potential of the provision of **ammonia** (B-02 and Z-02) is reduced by approximately 45% through the use of renewable electricity and exhaust gas purification, reaching the level of the fossil fuel reference.

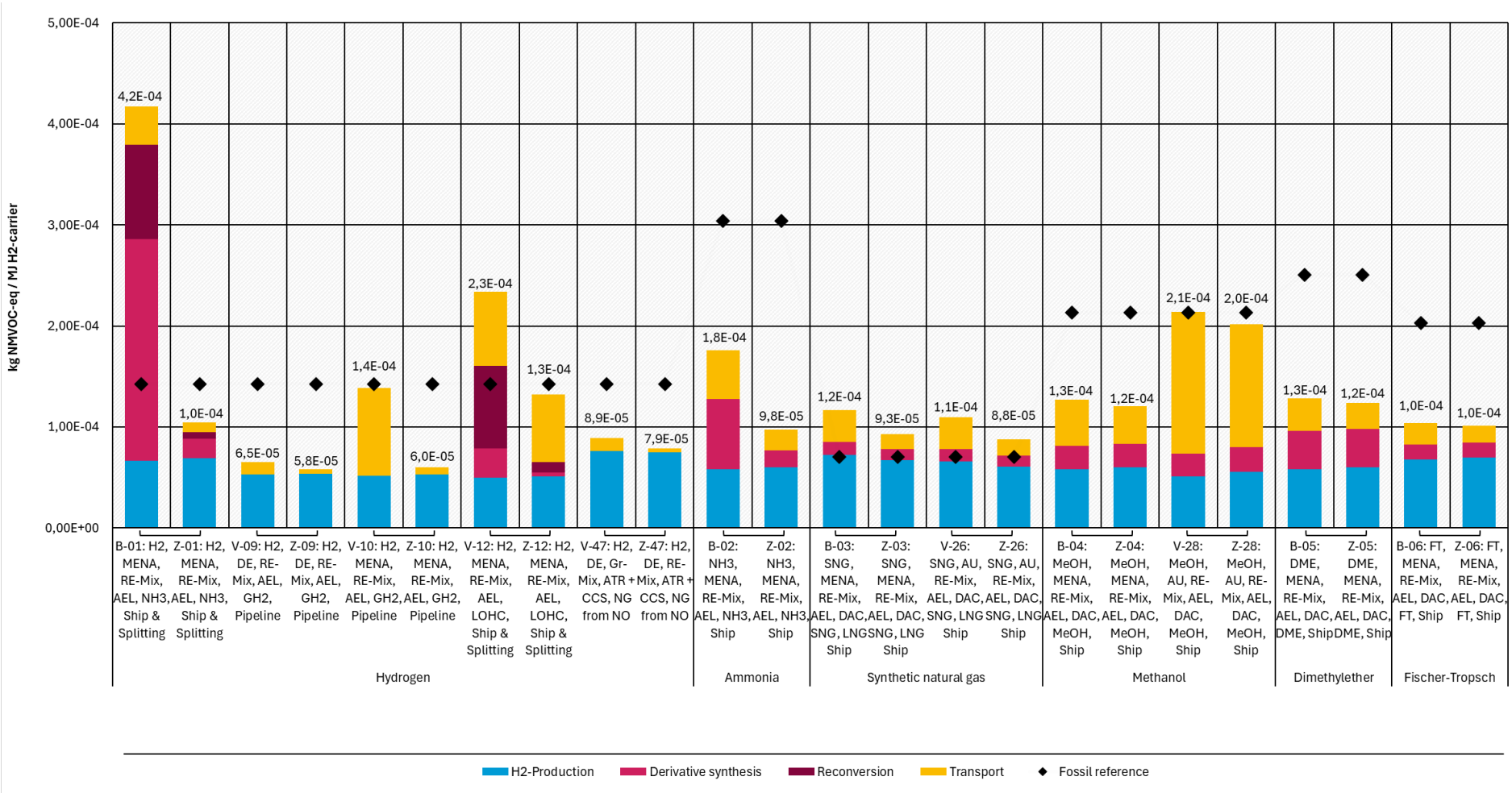
In the cases of **hydrogen**, the use of renewable electricity for the synthesis and splitting of NH_3 as a transport medium (Z-01), the operation of pipelines (Z-09, Z-47), LOHC production and reconversion (Z-12) results in a reduction in the contribution to summer smog potential, so that in all cases lower values than those of the fossil reference can be achieved.

The summer smog potential of supplying **ammonia** (B-02 and Z-02) is reduced by approx. 40% through the use of renewable electricity and exhaust gas purification, amounting to only about 1/3 of the fossil reference.

The provision of **SNG** results in reductions in summer smog potential of approximately 20%, in particular through the use of renewable electricity for liquefaction instead of SNG-powered turbines, which means that less SNG needs to be produced.

All **other PtGLS products** result in reductions in summer smog potential of approximately 2-6%, which are composed of the lack of emissions from heavy fuel oil production, lower SO_2 emissions during transport through the use of PtGLS fuels, and the reduction of NMVOC emissions through the use of electric trucks.

Figure 52: Summer smog category – Comparison of base cases, variants and target scenarios for selected pathways.



Base case /variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.6 Particulate matter

Direct emissions of particulate matter into the air and air emissions of the precursor substances nitrogen oxides (NO_X), sulphur dioxide (SO_2) and ammonia (NH_3) contribute in particular to the particulate matter (PM2.5) category. Figure 53 shows the results of the target scenarios in the particulate matter category compared to the corresponding base cases and variants.

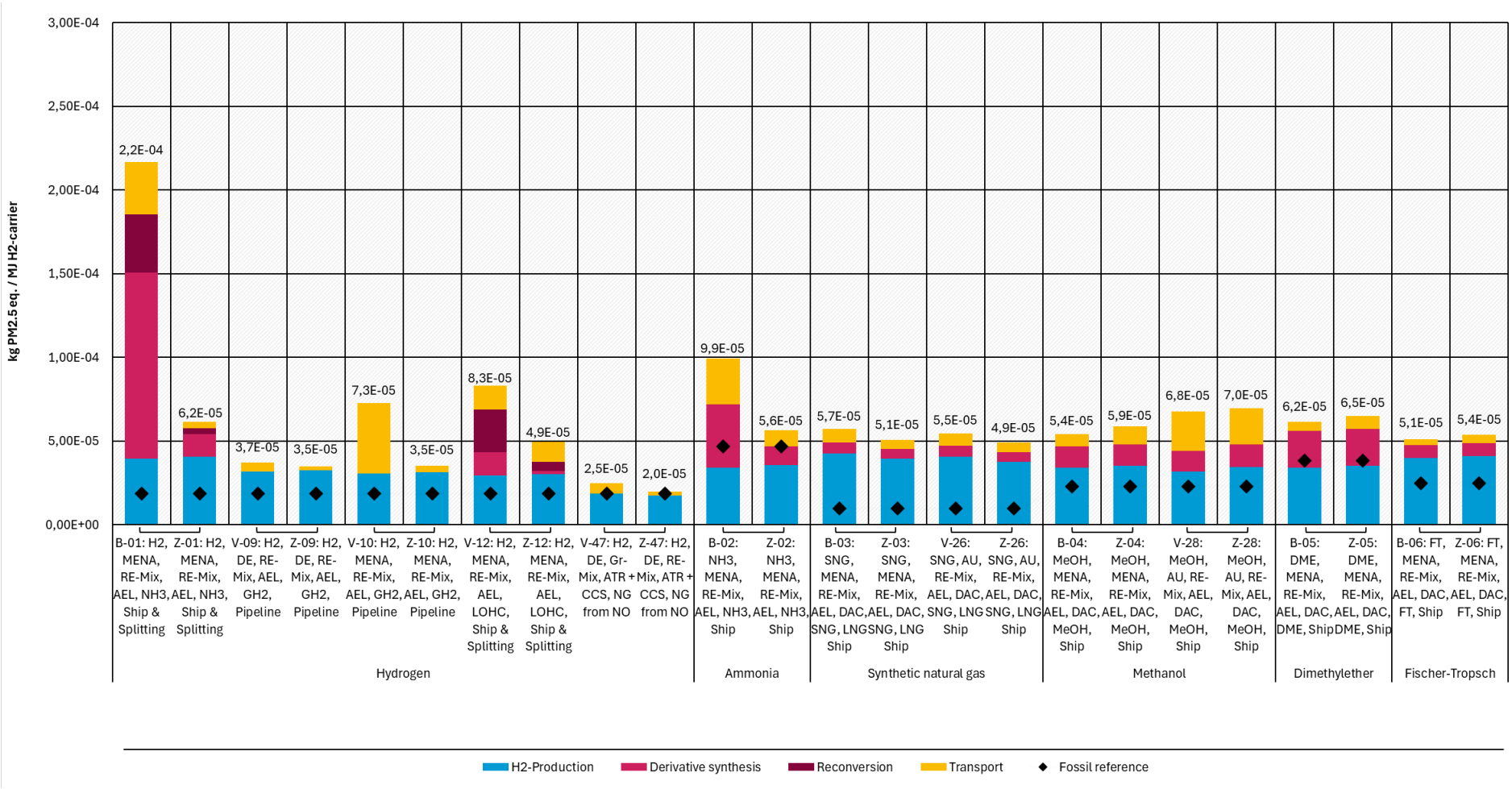
In the **hydrogen** cases, the use of renewable electricity for the synthesis and splitting of NH_3 as a transport medium (Z-01), the operation of pipelines (Z-09, Z-47), and LOHC production and reconversion (Z-12) results in a reduction in particulate matter formation potential, so that in most cases values are achieved that are approximately 90% above the fossil reference. NH_3 and LOHC as hydrogen carriers are exceptions. Ammonia emissions from NH_3 synthesis continue to contribute to particulate matter formation. For LOHC, the need for catalysts and electricity for loading and reconversion, as well as its low density during transport, lead to increased values (165% above the fossil reference).

The particulate matter formation potential of the provision of **Ammonia** (B-02 and Z-02) is reduced by approximately 45% through the use of renewable electricity and exhaust gas cleaning, reaching the level of the fossil reference.

The provision of **SNG** results in reductions in the particulate matter formation potential of approximately 10%, in particular through the use of renewable electricity for liquefaction instead of SNG-powered turbines, which means that less SNG needs to be produced.

For all **other PtGLS products**, there are slight increases in particulate matter formation potential in the range of 3-8%, which are composed of SO_2 emissions from seawater desalination, the additional demand for hydrogen to produce the fuel, and a contribution from the production of electric trucks.

Figure 53: Particulate matter category – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.7 Cumulative energy demand (CED)

Figure 54 shows the results of the target scenarios in the cumulative energy demand category compared to the corresponding base cases and variants.

In the **hydrogen** cases, a reduction in cumulative energy consumption is achieved through the use of renewable electricity to operate pipelines (Z-09, Z-10, Z-47) and to produce and reconvert ammonia and LOHC (Z-01, Z-12). The energy consumption for electrolysis has not changed, but there is an almost imperceptible increase in the CED due to the additional electricity consumption for seawater desalination. In cases involving longer transport distances (MENA, AU) in particular, this results in reductions in cumulative energy consumption of approximately 15%.

The provision of **ammonia** results in a slight increase in the CED due to the additional electricity consumption for seawater desalination. Since the base scenario B-02 already assumed that ammonia synthesis would be supplied with renewable electricity, there are no additional effects in the derivative synthesis.

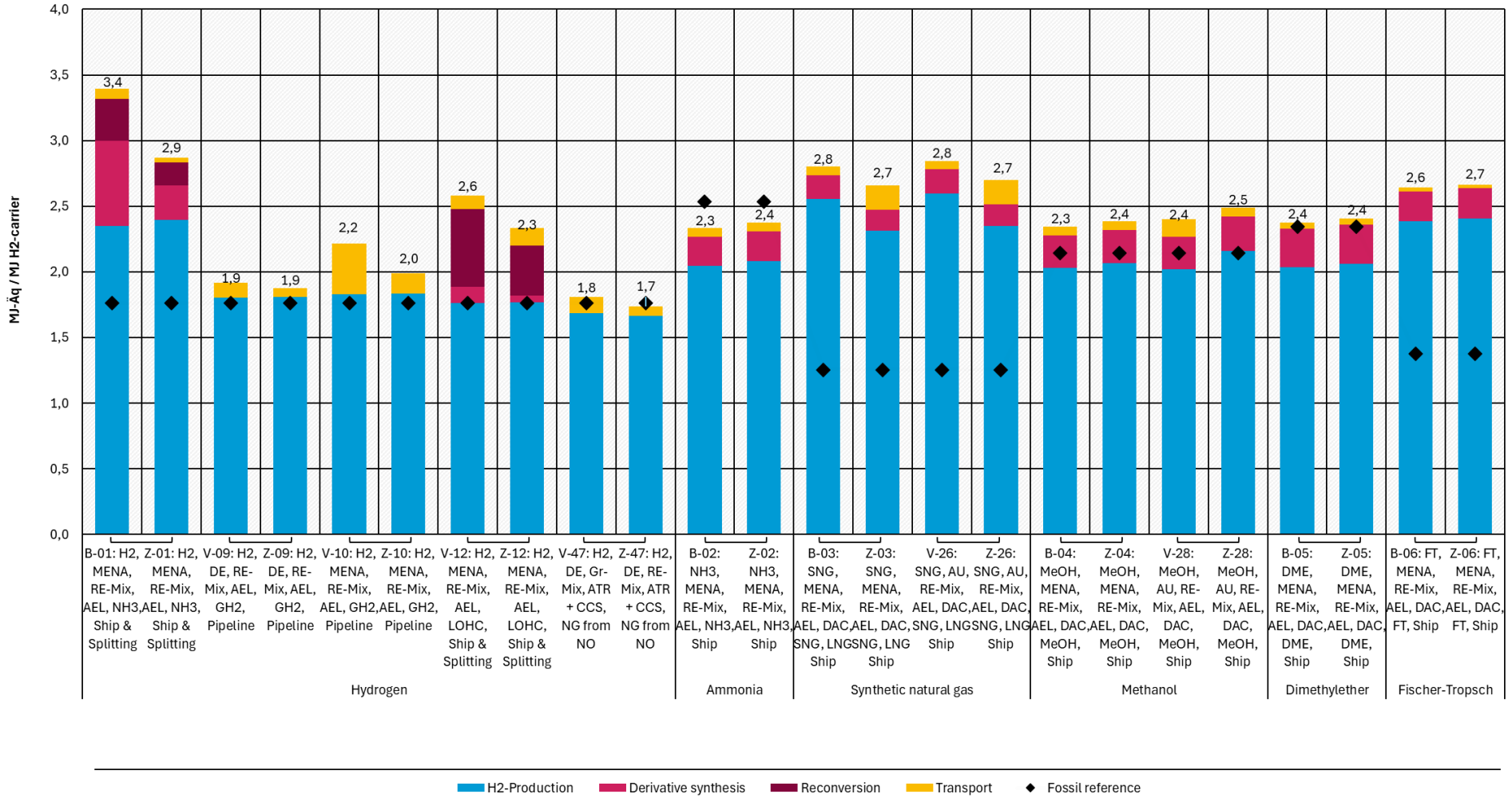
The provision of **SNG** results in a reduction in CED of approximately 5%. The measures implemented include the use of renewable electricity to liquefy SNG instead of burning SNG in a gas turbine. This results in a shift in the categories:

- In the base case B-03 (and also in V-26), additional SNG is produced for energy generation for the liquefaction of SNG, and additional hydrogen is generated for this purpose. This hydrogen generation is assigned to the category "H_2 generation", and the corresponding additional expenditure for synthesis is assigned to the category "derivative synthesis".
- In target scenarios Z-03 and Z-26, renewable electricity is used for liquefaction and less SNG is produced for this purpose. This reduces the energy consumption in the categories "H_2 production" and "derivative synthesis" accordingly. However, the electricity required for liquefaction is allocated to the "transport" category, which increases as a result.

Since the production of SNG is less efficient than the direct use of renewable electricity, this results in an overall reduction in the CED.

For all **other PtGLS products**, there are slight increases in CED due to the additional hydrogen required to produce the fuel.

Figure 54: Category Cumulative Energy Consumption (CED) – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.8 Hemeroby-weighted land use

Figure 55 shows the results of the target scenarios in the category of hemeroby-weighted land use in comparison to the corresponding base cases and variants.

Land use is dominated by hydrogen production in all cases except for the provision of "blue" hydrogen (V-47 and Z-47) – primarily due to the land required for renewable electricity generation. No measures to reduce land use were assumed in the target scenarios, nor were any measures to use already sealed areas instead of near-natural areas. Therefore, no reduction in hemeroby-weighted land use was to be expected.

In the **hydrogen** cases, there is an increase in land use of between 3 and 10% due to the use of renewable electricity for ammonia synthesis (Z-01), the operation of pipelines (Z-09, Z-10) and for LOHC production and reconversion (Z-12).

The provision of "blue" hydrogen (V-47, Z-47) has a hemeroby-weighted land use that is around an order of magnitude lower, as predominantly fossil fuels with low land requirements are used. In target scenario Z-47, there is a reduction in land use in transport because the baseline scenario V-47 includes electricity generation from cultivated biomass in the German electricity mix, whereas the target scenario with renewable electricity no longer does.

The provision of **ammonia** results in an increase in land use of approximately 3% due to additional renewable electricity in transport.

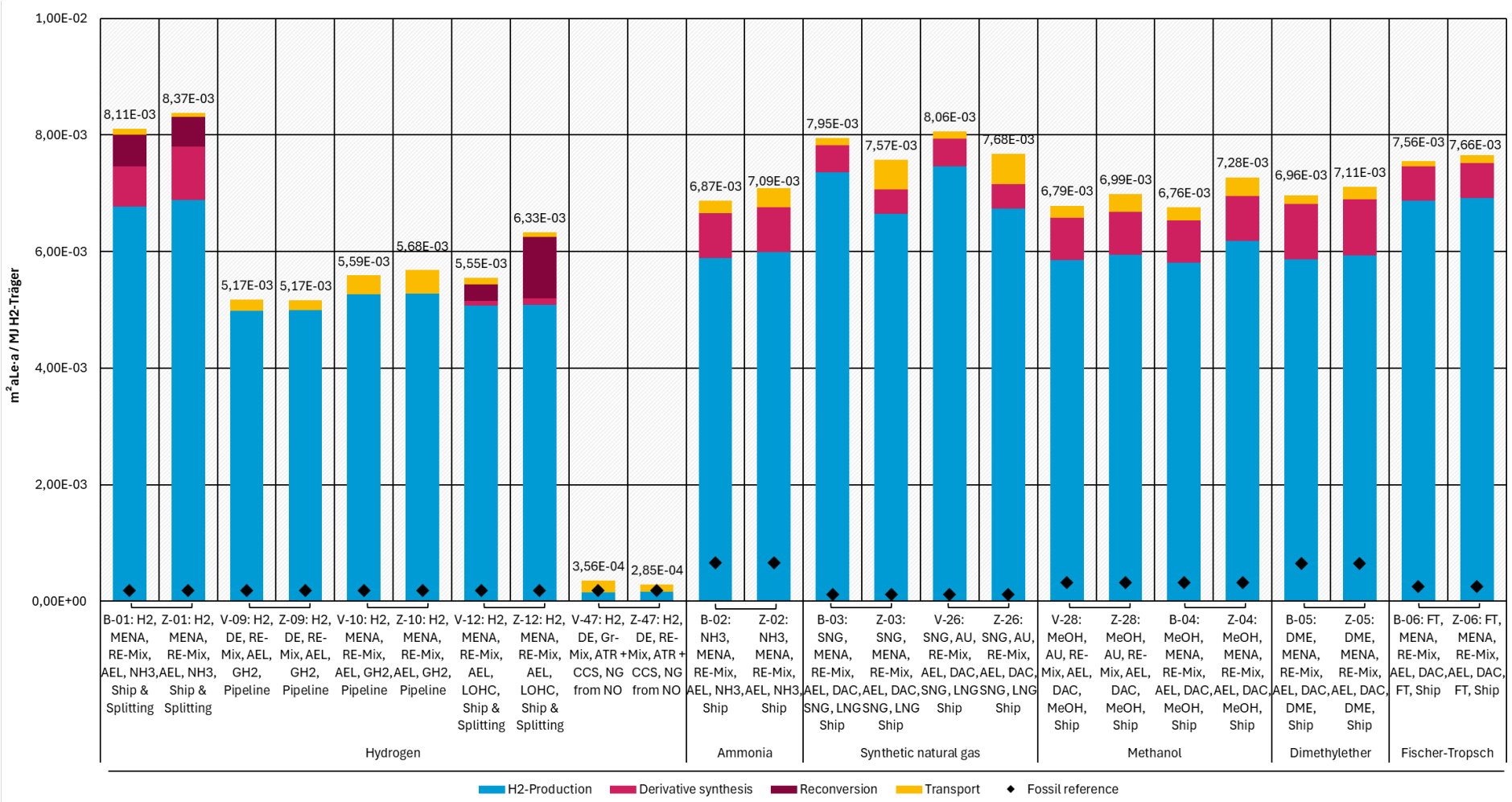
The provision of **SNG** results in a reduction in land use of approximately 5%. The measures implemented include the use of renewable electricity to liquefy SNG instead of burning SNG in gas turbines. This results in a shift in the categories:

- In the base case B-03 (and also in V-26), additional SNG is produced for energy generation for the liquefaction of SNG, and additional hydrogen is generated for this purpose. This hydrogen production is assigned to the category "H_2 production", and the corresponding additional expenditure for synthesis is assigned to the category "derivative synthesis".
- In target scenarios Z-03 and Z-26, renewable electricity is used for liquefaction and less SNG is produced for this purpose. This reduces the land requirement in the categories "H_2 production" and "derivative synthesis" accordingly. However, the electricity required for liquefaction is allocated to the "transport" category, which increases as a result.

Since the production of SNG is less efficient than the direct use of renewable electricity, this results in an overall reduction in land requirements.

For all **other PtGLS products**, there are slight increases in land requirements due to the additional demand for PtGLS products as marine fuel and the production and operation of electric trucks.

Figure 55: Category: Hemerobic-weighted land use – comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.9 Water demand

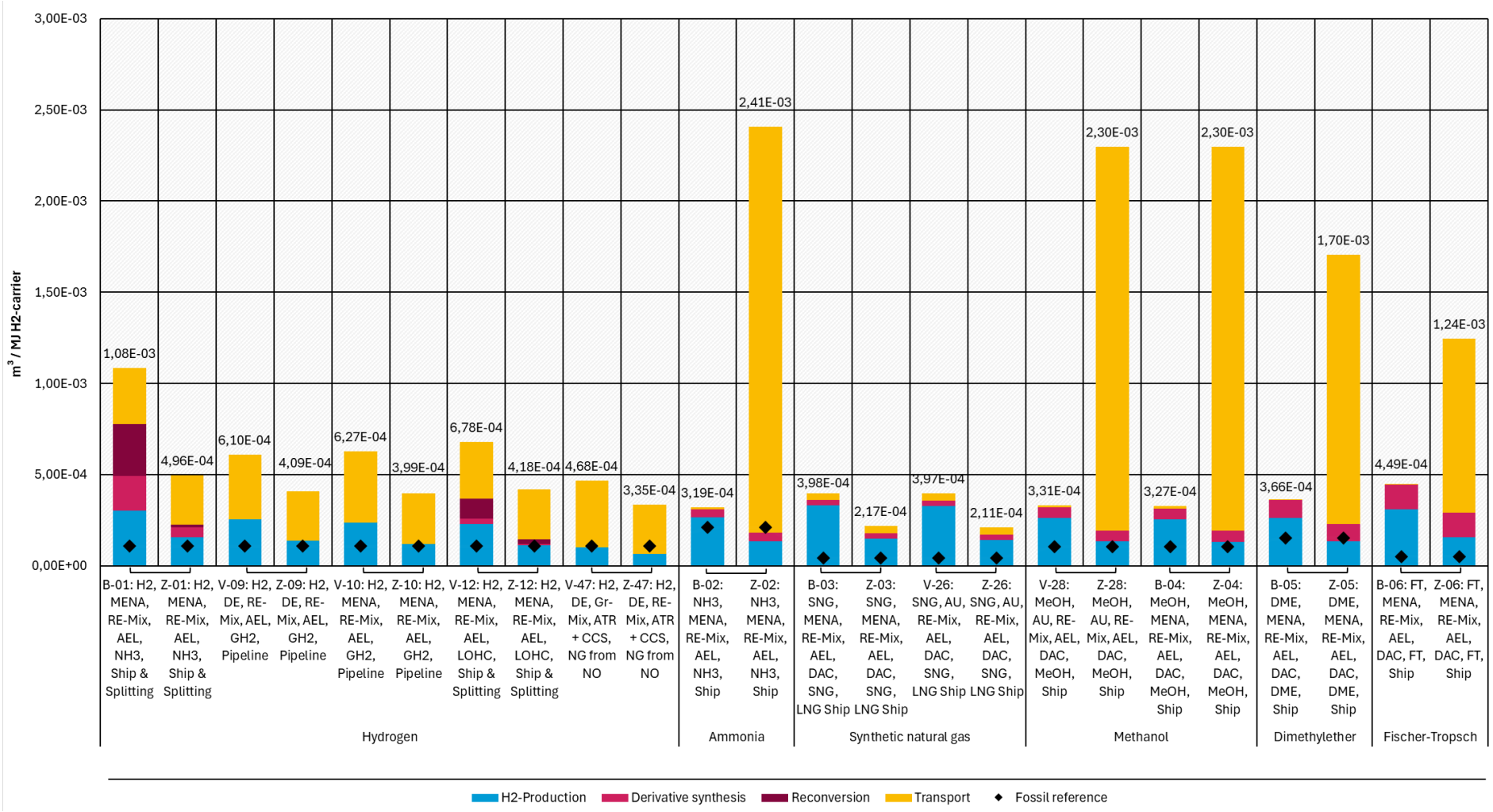
Figure 56 shows the results of the target scenarios in the water demand category (freshwater input at the balance level) compared to the corresponding base cases and variants. All target scenarios without truck transport show significant reductions in water demand compared to the respective reference cases.

In general, a reduction in freshwater demand of approximately 50% is achieved through seawater desalination for electrolysis in all PtGLS products. In derivative synthesis, reconversion and ATR, the switch to renewable electricity results in reductions in water demand, although some of the reductions are offset by the additional demand for PtGLS as marine fuel. The reduction in water demand for H_2 as a product is 30–50% across the various pathways.

Significant additional consumption results from the transport of PtGLS products other than hydrogen and SNG when distributed by electric trucks. This is based on increased water consumption for vehicle construction and battery production, which leads to a total of up to six times higher consumption. However, this trend contradicts the results of the UBA research project UAAK (Biemann et al. 2024), which found that electric trucks consume six times less fresh water than conventional diesel trucks. The discrepancies can be attributed to differences in the data used.

Ultimately, all cases are above the fossil fuel reference values, although there is also uncertainty here as to whether all relevant water requirements have been consistently taken into account in the ecoinvent database (ecoinvent 2024; Wernet et al. 2016).

Figure 56: Category water demand – comparison of base cases, variants and target scenarios for selected paths.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.3.2.10 Resource use ($ADP_{elements}$)

Figure 57 shows the results of the target scenarios in the resource use category compared to the corresponding base cases and variants. For all target scenarios, the results are either unchanged or significantly higher than the respective reference cases, with the exception of SNG, where there is a significant reduction in resource requirements.

In the variants for **hydrogen**, there are hardly any changes in resource consumption. Slightly higher contributions in H_2 production result from the increased energy requirements for seawater desalination. Higher contributions in transport (Z-01, Z-09, Z-12 and Z-47) result from the switch to renewable electricity in Germany in short-distance pipelines. In Z-10, on the other hand, the opposite is true, as fossil-based electricity in the MENA region requires more resources than a renewable energy mix designed for the long-distance transport of H_2 via pipeline.

A similar trend emerges for derivative synthesis and reconversion in Z-01 and Z-12. While the ADP of derivative synthesis in the target scenarios decreases due to the use of renewable electricity in the MENA region, it increases for reconversion due to the use of renewable electricity in Germany.

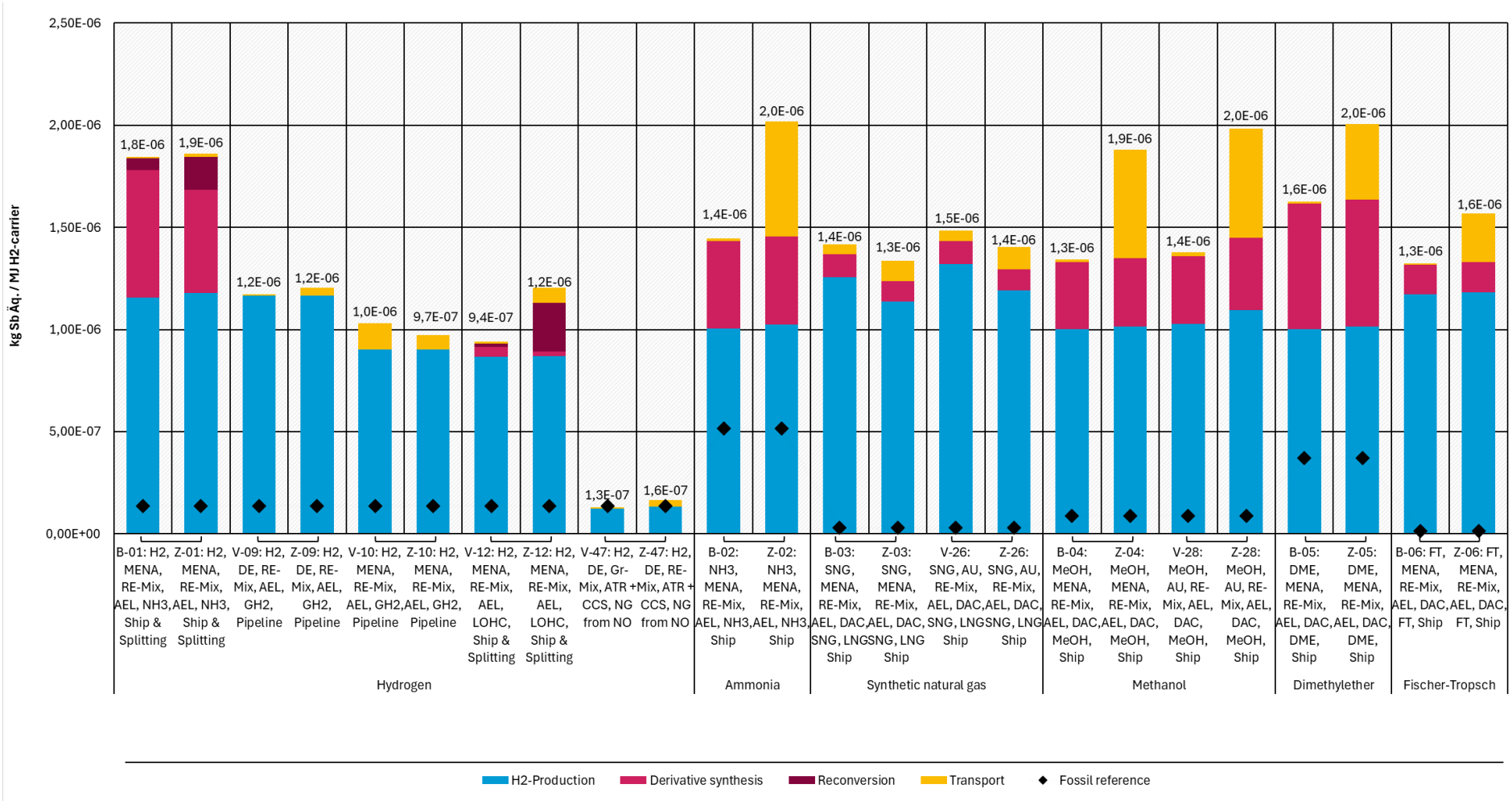
The provision of **SNG** results in a reduction in resource consumption of approximately 6%. The measures implemented include the use of renewable electricity to liquefy SNG instead of burning SNG in a gas turbine. This results in a shift in the categories:

- In the base case B-03 (and also in V-26), additional SNG is produced for energy generation for the liquefaction of SNG, and additional hydrogen is generated for this purpose. This hydrogen production is assigned to the category "H_2 production", and the corresponding additional expenditure for synthesis to the category "derivative synthesis".
- In target scenarios Z-03 and Z-26, renewable electricity is used for liquefaction and less SNG is produced for this purpose. This reduces the energy consumption in the categories "H_2 production" and "derivative synthesis" accordingly. However, the electricity required for liquefaction is allocated to the "transport" category, which increases as a result.

Significant additional consumption results from the transport of **PtGLS products** other than hydrogen and SNG when distributed by electric trucks. Here, increased resource requirements for vehicle construction and metals/minerals in battery production are assumed, leading to a total increase in demand of up to 40%.

Compared to the reference cases, none of the paths presented achieve a reduction in resource requirements.

Figure 57: Resource consumption category ($ADP_{elements}$) – Comparison of base cases, variants and target scenarios for selected pathways.



Base case/variant and corresponding target scenario shown side by side in pairs. Source: own representation, ifeu.

5.4 Uncertainties in the data

The calculated environmental impacts are uncertain insofar as, although energy and raw material requirements are published for many of the production facilities examined here, precise details of direct emissions of environmentally harmful substances are rarely provided. The calculated results therefore contain almost no environmental impacts from direct emissions from the processes in the foreground system (for data, see process descriptions in section 2 or in the Excel table in the technical appendix).

This uncertainty can initially be considered to be of little relevance to the overall environmental impact, as industrial plants at sites in Germany are subject to strict regulations governing the emission of pollutants into the air and water. These regulations, which are based on the Federal Immission Control Act (BImSchG) and various ordinances, specify specific emission limits and monitoring obligations.

However, for imports of PtGLS products manufactured abroad, where these limits may not have been set by law or may be significantly higher, individual emissions could contribute significantly to the result. The following is therefore recommended:

- Emission regulations that apply in Germany should also be prescribed for corresponding PtGLS manufacturing processes abroad for imports into Germany – unless these are equal or already stricter there.
- Production facilities should be required to regularly measure and report relevant emissions, unless this is already required by existing regulations. The following emissions are particularly important in this context:
  - Carbon dioxide, carbon monoxide (CO_2, CO)
  - Hydrogen (H_2)
  - Methane (CH_4)
  - Ammonia (NH_3)
  - Nitrogen oxides (NO_x, N_2O)
  - Sulphur dioxide (SO_2)
  - Particulate matter
  - Volatile organic compounds (VOC)
  - Heavy metals
  - Fluorinated and polyfluorinated substances (PFAS, PFOS)
- Even for processes for which direct emissions are quantified in the literature, there are uncertainties – especially when it comes to technologies that are not yet widely established. One example of this is the use of ammonia as a (shipping) fuel and the division in its use as a hydrogen carrier. The data for these emissions has so far only come from technology studies and pilot projects (Alghool et al. 2024; Kanchiralla et al. 2022). At the same time, the potential environmental impacts associated with these emissions are significant (Bertagni et al. 2023).

- Development of guidelines on Best Available Techniques (BAT) for processes along the PtGLS production chain, if these do not already exist (e.g. for ammonia synthesis, steam reforming of methane, industrial cooling systems)
- Certify supply chains on this basis and make all steps transparent.

5.5 Conclusions

The previous sections identified the main environmental impacts of the provision of various PtGLS fuels (section 5.1), proposed technical measures to mitigate these environmental impacts (section 5.2) and quantified the resulting mitigation effects and countervailing effects, i.e. potentially increased environmental impacts in other impact categories (section 5.3). This section summarises the results and identifies the measures considered necessary for a sustainable supply of PtGLS products.

Section 4 already established that the provision of PtGLS products is less harmful to the climate than that of fossil reference products in most cases. The important influencing factors mentioned there were electricity supply, transport modes and transport distance. However, it was also shown that in other environmental impact categories, there are often increased impacts compared to the fossil reference. With the aim of further reducing the climate impact for all supply paths examined and at the same time reducing the most significant impacts in other categories, the technical measures proposed in section 5.2 were developed.

A comparison of the environmental impacts of the baseline scenarios and some of the variants from section 4 with the target scenarios described in section 5.3.1 above shows that, as assumed, the measures lead to an overall reduction in environmental impacts in the vast majority of the cases examined. Only a few measures lead to deteriorations in other impact categories. In most cases, these deteriorations are minor in comparison. The following section discusses the technical measures and their effects on the environmental impacts of PtGLS provision.

- **Renewable electricity supply** for all processes along the value chain (ATR/SMR, NH_3 synthesis, NH_3 and LOHC splitting, gas pipeline transport, etc.), including for heat supply, is important for reducing the climate impact. The energy transition is a basic prerequisite for ensuring that, in addition to electrolysis, all other processes can also be powered by renewable electricity.
  - In particular, supplying derivative synthesis and, where applicable, its reconversion with renewable electricity instead of grid electricity and fossil heat leads to major improvements in the categories of climate change, acidification and eutrophication.
  - The operation of gas pipelines and distribution networks with renewable electricity also leads to improvements, especially if the grid electricity used in the base case contains a high fossil proportion.
  - The direct use of renewable electricity in plants for the liquefaction of SNG is more effective than operation with gas turbines in which the previously produced SNG is burned. This reduces process related emissions in SNG synthesis.
  - The use of renewable electricity in all processes also leads to a reduction in environmental impacts in all other categories except for hemeroby-weighted land use, where slightly higher impacts occur.
- The use of carbon-based **PtGLS products as fuel** in shipping leads to savings in climate impact of 5-20%, depending on transport distance and energy source. At the same time, the

replacement of heavy fuel oil eliminates SO_2 emissions, reducing the impact of transport in the categories of acidification, summer smog and particulate matter. The additional electricity required to produce PtGLS fuel reduces this effect, but does not reverse it into a negative. The additional electricity requirement has negative effects in the categories of cumulative energy consumption and land use, but these are small in percentage terms compared to the reductions in the other categories.

- In all processes that produce or use **ammonia,** effective exhaust gas aftertreatment is important to eliminate emissions of nitrogen oxides and ammonia into the air.
  - The use of selective catalytic reduction (SCR) in exhaust gas aftertreatment in the processes for the production and splitting of ammonia can effectively reduce emissions of NO_X and NH_3. This leads to reductions in the environmental impact of these processes in the categories of acidification, eutrophication, summer smog and particulate matter of 70-90%.
- The use of **ammonia as a fuel** should be viewed critically based on current knowledge, as the following negative effects may occur:
  - According to current data, NH_3-powered marine engines produce climate-damaging N_2O emissions, which may more than offset the savings in fossil CO_2 emissions from the combustion of heavy fuel oil and can lead to higher climate impacts. There is uncertainty in the emission data used because ammonia engines are not yet in use (see section 5.4). In order to bring the environmental impact to a level comparable to other modes of transport, effective exhaust gas cleaning (SCR) is absolutely necessary.
  - An alternative is to use carbon-based PtGLS products as fuel for the transport of ammonia.
- The use of **seawater desalination** to obtain process water for electrolysis leads to significant savings in fresh water in hydrogen production. The additional electricity requirement is around 0.1% of the electricity required for electrolysis. Accordingly, there are slightly higher environmental impacts in all categories. Seawater desalination generates process-related emissions of SO_2 which lead to a slight increase in environmental impacts in the categories of acidification, summer smog and particulate matter. This study did not quantify the environmental impacts that may arise from the discharge of brine, the alteration of biodiversity in seawater or the use of antifouling and disinfectant agents.
- The use of **alternative membrane materials** without halogenated hydrocarbons, e.g. polysulphone membranes, significantly reduces the contribution to ozone depletion and has no identified negative effects in other impact categories.
- The use of **electrically powered lorries**, which are supplied with renewable electricity for the distribution of PtGLS products in Germany, leads to a reduction in the climate impact of transport. However, the manufacture of the truck, especially the battery, can lead to high additional burdens in the categories of resource requirements and water requirements, as well as a slight increase in the categories of eutrophication, ozone depletion and particulate matter. The effects are examined in detail in Biemann et al. (2024).
- The production of **"blue" hydrogen** requires a number of measures that can significantly reduce its climate impact:

- **Minimising methane losses** during the extraction, transport and storage of natural gas is crucial for the climate impact. This has already been shown in section 4.3.1.2 based on the different climate impacts of natural gas from different producing countries. Production conditions can lead to a variation in the climate impact of "blue" hydrogen by a factor of more than two.
- When selecting the reformer technology, the **autothermal reforming (ATR)** process is preferable to steam reforming (SMR) in terms of CO_2 capture options. Higher capture rates can be achieved through energy generation within the reactor, thereby reducing the climate impact.
- **A high** possible **separation rate for CO_2** from the product stream of the reformer is also important for a low climate impact. The target should be a separation rate of 98%.
- The **permanent storage of the captured CO_2** without leaks or spills due to accidents or other events is an essential prerequisite for "blue" hydrogen to achieve the low climate impact shown. Storage requires suitable storage sites, which are only available to a limited extent. These must be monitored for thousands of years, and the storage space excludes alternative uses like raw material extraction, deep geothermal energy, wind turbines, etc. for an indefinite period (several tens of thousands of years).
- Additional reductions in climate impact can be achieved by supplying all processes with renewable electricity, with the additional reduced environmental impacts in other categories as described above.
- Only through the **combination of all these optimistic conditions** can "blue" hydrogen achieve a similarly low climate impact as "green" hydrogen. In many cases, the production of "blue" hydrogen will have a higher environmental impact than the optimal results shown in this study.

The measures examined in this study are aimed at direct changes in the so-called foreground processes, i.e. measures that plant operators can implement directly, or that distributors of PtGLS products, authorities or certification bodies can demand along the process chain for PtGLS products. This achieves a lower limit for climate impacts in the range of 14–24 g CO_2 eq./MJ. The other environmental impacts also have a limit that cannot be undercut with the proposed measures. Since the remaining environmental impacts originate from the so-called background system, they cannot be addressed by measures taken in the process chains for the production of PtGLS products themselves. In order to address these environmental impacts, processes in the background system must be defossilised and improved in other aspects as well in order to reduce the environmental impacts of the overall system. This includes, in particular, the production of cement, steel, aluminium, copper, glass and plastics. This includes alternative manufacturing processes, e.g. steel production via direct reduction with hydrogen (DRI process) and increasing the proportion of secondary materials, as well as the consistent defossilisation of energy supply through the efficient use of renewable electricity (e.g. heat through electric heating or the combustion of PtGLS products, the highest possible degree of electrification in the transport sector or the use of PtGLS products) (Dittrich et al. 2025).

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