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System comparison of storable energy carriers from renewable energies

Final report

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System comparison of storable energy carriers from renewable energies

Final report

by

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Abstract: System comparison of storable energy carriers from renewable energies

In the course of the transformation to a greenhouse gas-neutral society in the second half of the 21st century, the use of synthetic energy carriers based on renewable electricity or biomass is under discussion. This project evaluates the environmental impacts of technical and logistical options for the generation of such energy carriers on the basis of environmental impact categories such as global warming potential, acidification or land use. The production of five products (Fischer-Tropsch fuels, methanol, synthetic natural gas, biomethane and hydrogen) was examined based on various process steps/procedures and their current and future technical data. By using regional factors for Germany, Europe, and the Mediterranean region - like the availability of renewable energy carriers such as wind or PV and of raw materials such as carbon or water as well as transport routes to Germany - these processes were combined to form supply paths for these energy carriers. Using the method of life cycle assessment, the environmental effects were analysed for today and 2050. In addition, the costs for plant construction and operation were estimated. The results show that synthetic energy carriers generally have a significantly lower global warming potential than today's fossil reference products due to the use of renewable energies. However, the production of electricity generation plants and associated economic processes - such as steel and cement production - can still make a relevant contribution to the global warming potential if they are not also greenhouse neutral. At the same time, it is this production of the necessary plants that leads to (sometimes significantly) increased burdens compared with the fossil reference in almost all other impact categories, most notably in terms of water and land use. This study therefore also provides indications of which environmental impacts must be further reduced in the future.

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List of abbreviations

AEL	Alkaline Electrolysis
CHP	Combined Heat and Power
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit)
BtL	Conversion of biomass to liquid secondary energy carriers (Biomass-to-Liquid)
CSP	Concentrating Solar Power
DAC	CO_2 -separation from air (Direct Air Capture)
Destatis	Federal statistical office, Wiesbaden
EUMENA	Europe and MENA (Midlle East and North Africa)
FT	Fischer-Tropsch
GWP	Global Warming Potential
HVDC	High Voltage Direct Current transmission
HTEL	High Temperature ELectrolysis
LHV	Lower Heating Value
MENA	Middle East and North Africa Region
MeOH	Methanol
WIP	Waste Incineration Plant
PBtL	Conversion of electricity and biomass to liquid secondary energy carriers (Power-Biomass-to-Liquid)
PEM-EL	Proton Exchange Membrane ELectrolysis (also: Polymer Electrolyte Mem-brane ELectrolysis)
PtG	Conversion of electricity to gaseous secondary energy carriers (Power-to-Gas)
PtL	Conversion of electricity to liquid secondary energy carriers (Power-to-Liq-uids)
PtX	Here: Conversion of electricity to liquid or gaseous secondary energy carriers (Power-to-X)
PV	Photovoltaics
RED	Renewable Energy Directive
(r)WGS	(reverse) Water Gas Shift reaction
SNG	Synthetic Natural Gas
TRL	Technological Readiness Level
UBA	Federal Environment Agency, Germany (Umweltbundesamt)
FLH	Full load hours

1 Motivation and objectives

The Paris climate accord of December 2015 implies nothing less than the complete climate neutrality of our material economy in the second half of the 21st century. Germany has committed itself to reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990. The reduction target for the year 2050 is between 80 und 95%.

For most consumption sectors, the direct use of electricity from renewable energy sources is the most environmentally friendly and efficient way of supplying energy. However, in some sectors, such as for long-distance transport (air transport, international shipping, lorries, partly passenger cars) and in industry (e.g., as raw material, reducing agent and fuel), liquid or gaseous energy carriers will probably remain necessary.

This demand can be met by gaseous and liquid energy carriers based on renewable electricity and, to a lesser extent, on biomass. The UBA study "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE" [UBA 2019] estimates the demand for gaseous energy carriers and liquid hydrocarbons for the year 2050 at 500 to 1,000 TWh, depending on the scenario; the net electricity requirement for this is estimated at 1,000 to 2,000 TWh. The energy demand is thus more than twice as high as the electricity production for direct electricity use in the same scenarios. According to current estimates, the required amount of renewable electricity cannot be generated in Germany alone due to the lack of suitable locations for efficient electricity generation. It must therefore be assumed that in the future, electricity or synthetic energy carriers for Germany will also have to be produced in third countries to cover demand. This could also be advantageous from an economic perspective.

Despite the use of renewable energies, the supply of storable energy carriers causes environmental impacts, since the manufacture of the plants and the construction of the transport infrastructure are associated with relevant energy and resource consumption as well as air and water emissions. If cultivated biomass is used to produce the storable energy carriers, further specific environmental burdens from agriculture and forestry are to be expected at local level (e.g., in terms of soil quality, land use, direct land use change) and supraregional impacts (e.g., water eutrophication, indirect land use change, GHG).

Within the framework of this project, information has been compiled which describes different technical and logistical possibilities to provide gaseous and liquid energy carriers which are produced from renewable electricity or biomass. Production in Germany and abroad in regions with more favourable conditions for renewable electricity generation was investigated.

The basis for the comparison of supply options is the life cycle assessment method, which takes into account all relevant environmental impacts and resource requirements (raw materials, energy, water, land) for the reference years 2015, 2030 and 2050. The results of the research project are intended to create a scientific basis for the most sustainable and efficient supply of these energy carriers. In order to obtain a broad overview of possible locations and supply paths, ecologically unfavourable variants were deliberately included. This makes it possible to show ranges and identify potentially unfavourable development paths.

This study does not sketch a scenario for the supply of the German economy with storable energy carriers from renewable energies. Nor are any recommendations given for the use of specific sites outside Germany. The aim is to investigate and present the influence of selected energy and carbon sources and other parameters (e.g., for transport costs and location factors) on the environmental effects of such energy carriers.

The following chapter 2 gives an overview of the methodological approach. Chapter 3 presents the main results. Details of the individual research steps and of the results can be found in the annex to this report.

2 Overview of procedures and methods

The supply paths for hydrogen, synthetic natural gas and synthetic liquid hydrocarbons based on biomass and electricity from renewable energies were described, characterised and evaluated in a multi-stage process.

First, individual relevant process steps/procedures were defined in the form of modules and their electricity and estimated future technical data were documented. The nature of the systems under consideration and the large reference period of the LCA analysis – 2015 to 2050 – led to methodological challenges. The processes of energy supply and conversion are partly still in early development phases. Some of the process data are therefore subject to uncertainties. For example, technologies already available on the market (e.g., Fischer-Tropsch synthesis of liquid hydrocarbons from synthesis gas) stand alongside others for which the first demonstration plants exist (e.g., direct methanisation of CO_2). The final descriptions of the individual supply paths therefore list the respective technology readiness levels (TRL).

In a second step, location factors were considered in order to be able to assume plausible transport distances and routes as well as full load hours of the power source for the supply paths.

In the next step, the modules were combined into technically useful paths. Simplified overview LCAs then made it possible to identify both particularly disadvantageous and particularly favourable supply paths. The modular structure allowed to explore the influence of different production steps and technology options and possible combinations on the overall result.

From the large number of possible combinations, those supply paths were then selected which cover the broadest possible field: On the one hand, many different technical options for producing the energy sources are to be investigated. On the other hand, the paths from which particularly large or particularly small environmental impacts were to be expected were to be included.

The selected paths were finally analysed using the life cycle assessment method.

2.1 Products, processes, sources of electricity and raw materials

A detailed description of the selected technologies and all data sources on which their descriptions are based can be found in the fact sheets in chapter 2 of the annex to this report.

2.1.1 Products

The products selected for this project were:

- Hydrogen
  Hydrogen is expected to play an important role in a greenhouse gas neutral economy - as a fuel, reducing agent and raw material.
- Fischer-Tropsch fuel
  Liquid hydrocarbons such as naphtha, diesel, petrol, and paraffin will continue to be able to be used wherever they are already in use today - as fuel, combustibles and as a raw material in the chemical industry.
  Since the process steps for the various products only differ in detail, they are combined to form an average fuel named after the Fischer-Tropsch synthesis.
- Methanol

Methanol is one of the most important basic materials for the chemical industry and can be used either directly or by further processing (e.g., to dimethyl ether (DME)), among other things as a fuel.

- Synthetic natural gas and biomethane
  Thanks to their chemical properties, these gases can seamlessly take over the role of fossil natural gas today - as a fuel, a combustible and as a raw material in the chemical industry.

2.1.2 Production process

Hydrogen

In electrolysis, water molecules are decomposed into gaseous hydrogen and oxygen by means of direct electric energy. Water electrolysers can be divided into three relevant types according to the type of electrolytes used:

- The alkaline electrolysis (AEL) with aqueous potash or sodium hydroxide as electrolyte,
- the polymer electrolyte membrane electrolysis (PEMEL) with a proton-conducting membrane as electrolyte and
- the solid oxide high temperature electrolysis (HTEL) with a ceramic ion conducting membrane.

Theses electrolysis technologies have different levels of technological readiness. Data on production and operation are taken from the literature and the project participants' own research work.

Liquid hydrocarbons and methanol

The modules for the provision of synthetic liquid energy sources concentrate on the two technology strands Fischer-Tropsch synthesis and methanol synthesis.

The technology data are largely based on projects carried out at the German Aerospace Centre. Based on extensive literature research, the respective processes were mapped with the help of the process simulation software AspenPlus and also economically optimised through coupling with the techno-economic evaluation tool TEPET. The results allow a comparison of the individual process chains, as the applied procedure is based on standardised methods of the chemical industry.

Gaseous hydrocarbons

The gaseous energy sources considered in this project are either produced as biomethane through the fermentation of biogenic raw materials and subsequent treatment, or they are produced through the direct methanisation of CO_2 and hydrogen. To produce biomethane, a number of biogenic substrates and purification processes were considered.

2.1.3 Electricity sources

The production of synthetic fuels is based to a large extent on energy input through electricity. It can be expected that the type of electricity generation will have a significant impact on the environmental impacts of the supply path, as the electricity generating plants differ widely in their production and the possible full load hours. A number of technologies have therefore been included:

- Wind turbines on land (Wind onshore)
- Wind turbines at sea (Wind offshore)

- Photovoltaics as rooftop systems, monocrystalline (PVroof)
- Photovoltaics as ground mounted systems, polycrystalline (PVground)
- Concentrating solar power plants (CSP) in various designs (parabolic trough, solar tower, with various heat storage units)
- Run-of-river power plants Central Europe
- Electricity from geothermal energy Iceland

Data for the manufacture and operation of the wind and PV plants were compared with the electricity UBA project " Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berück-sichtigung aktueller Technologieentwicklungen" [UBA 2019]. Other data sources are the ecoinvent 3.5 life cycle assessment database and completed research projects of the project participants.

2.1.4 Carbon sources

The production of synthetic liquid and gaseous hydrocarbons and methanol based on renewable electricity requires carbon sources. In addition to the carbon contained in biomass, carbon in the form of CO_2 in waste and flue gases is a particularly suitable source. Possible CO_2 sources are biogas plants, industrial processes and fossil power plants. But carbon dioxide can also be separated from the ambient air.

Data on the following separation technologies were compiled:

- CO_2 capture from biogas upgrading with
  - Pressure swing adsorption (PSA),
  - Pressure water scrubbing (PWS),
  - Polyglycol wash (Gensorb),
  - Membrane separation process,
  - Chemical scrubbing (MEA).

- Large-scale CO_2 capture from industrial and power plant waste gases with
  - Chemical scrubbing (MEA, MDEA),
  - Physical scrubbing (Selexol, Rectisol).

- Separation from the air in an adsorption process (DAC, direct air capture)

2.1.5 Biomass

A number of different biomasses were considered as substrates for the production of biogas by fermentation and as input for synthesis in the (Power&)Biomass-to-Liquid ((P)BtL) processes.

Data on the following biogenic residual and waste materials were compiled:

- Forest residue wood
- Liquid manure (slurry)
- Straw
- Biowaste
- Green waste / green cuttings
- Wood scarps

Data on the following cultivated biomasses have been compiled:

- Silage maize
- Wood from short rotation coppice
- Miscanthus

An explanation of how biomass is considered in this project in terms of availability, transportability and sustainability can be found in Chapter 2.2.2.

2.1.6 Water treatment

The production of hydrogen by electrolysis and the subsequent synthesis of gaseous and liquid energy carriers requires larger quantities of treated water. Furthermore, Fischer-Tropsch and methanol plants require the use of cooling and process water. This water demand must be covered either by treated surface or ground water or by desalinated seawater.

Within the scope of this project, data on the following treatment technologies were collected:

- Water treatment of surface and ground water with reverse osmosis and ion exchangers,
- Seawater desalination with reverse osmosis.

2.1.7 Transport options

To be able to ecologically assess the supply of electricity or synthetic energy sources in Germany, their transport must be taken into account. This is particularly relevant if they are not produced in Germany. There are basically two options:

- Transport of electricity to Germany and production of the energy sources on site; or
- Production of the fuels abroad with subsequent transport to Germany.

High voltage direct electricity transmission lines (HVDC) were considered for the transport of electricity over long distances, while fuels can be transported by ship and truck. Gas can also be transported via pipelines.

2.2 Location factors

In addition to technological parameters, site-specific factors were also needed to define and study the supply paths of synthetic energy sources. For a pre-selection of the supply paths to be analysed, essential regional differentiations were considered, and a characterisation of site factors was carried out in order to work out possible advantages of a site.

The following chapter provides a brief overview of the procedure. The detailed description and all the data sources used for this purpose can be found in chapter 4 in the Annex to this report.

The inputs electricity, carbon - also from biomass - and water were identified as essential location factors. These factors were analysed qualitatively and semi-quantitatively. The aim of the analysis was to identify countries with high-value location factors that can be assumed as starting point or production site in one of the supply paths.

In addition, the qualitative analysis of the factors served to characterise the process chains more precisely and thus to specify ecological and economic effects more precisely. For the provision of renewable electricity, the number of full-load hours at the respective location was relevant from a cost and resource perspective. With regard to water as a resource, the decisive question was whether it was available in sufficient quantity at the location in question, or whether the supply paths would have to include additional water extraction from sea water.

Less relevant for the following analyses in this study were the total potentials of electricity, carbon and water available in absolute terms (see following chapters): In principle, the study compares supply paths without going into possible quantity structures. The aim of this part of the project was to identify the locations where, in relative terms, larger quantities of the sought-after resources are available. These sites could then become part of a supply path that was evaluated with regard to its ecological and economic characteristics.

The analysis includes Germany as well as regions in Europe, North Africa and the Middle East (EUMENA) as possible generation sites for exports of electricity or PtX- energy sources to Germany. The geographical delimitation is shown in Figure 1

Figure 1: Geographical system boundaries of the EUMENA region for this study

Source: DLR

2.2.1 Wind, PV and CSP

The largest economically exploitable renewable energy potentials available are sources with high spatial and temporal variability: wind on land and at sea (onshore and offshore) and solar energy (PV and CSP)

The supply paths for synthetic energy sources were mainly of interest in regions or locations with favourable conditions, which are characterised by high utilisation of installed capacity (high full load hours) and consequently favourable electricity generation costs. These regions were identified by spatially and temporally resolved GIS analyses of the renewable energy potential based on meteorological re-analyses and satellite data. However, in line with the project objectives, the concrete feasibility at specific locations was not examined. Instead, it was estimated which realistically possible full-load hours could be achieved on a large scale in the various regions. This follows the assumption that in energy systems with a very high share of renewable energies not only the best but also a broad range of favourable locations have to be used.

The analysis was based on the REMix-EnDAT energy system model developed at DLR, which can be used to determine potentials adapted to the requirements of storable energy sources [Stetter 2014]. Initially, these requirements, e.g., regarding minimum full load hours and grid connection had to be identified. On this basis, spatially resolved electricity potential maps were generated from globally available data sets. Finally, the results were potentials for wind and solar energy (PV/CSP) at country level depending on the selected parameters. No precise sites were selected for the supply paths in this project, but rather the data for an averaged, good location in a country were used. For this purpose, full-load hour potential curves were drawn up for individual countries. The lower 50% of the potential (i.e., the bad sites) were then cut off. The mean of the full-load hours of the remaining upper 50% of potential was used as an input into the calculation. Table 1 shows the full-load hours thus determined for some selected countries and technologies.

Table 1: Mean full load hours for the upper 50% of full load hour potential curves for some selected countries and technologies

Country	PVground	CSP	CSP SM3	Wind Onshore	Wind Offshore
Morocco	1,729	2,063	6,189	2,946	3,928
Saudi Arabia	1,777	2,179	6,537	1,870	1,963
Germany	958	0	0	2,963	4,234

PVground: photovoltaic systems ground mounted, CSP (SM3): concentrating solar power (with solar multiple 3 = 14 h storage) Wind Onshore/Offshore: Wind turbines on land/at sea

2.2.2 Biomass

Sufficient input must also be ensured for the biomass-based technology modules to produce liquid and gaseous hydrocarbons. On the one hand, these is solid biomass, especially for the BtL and PBtL supply paths, and on the other hand, the supply of gaseous hydrocarbons from fermentation requires corresponding quantities of biogas substrates. The data collected serve exclusively to select plausible starting points for biomass-based supply paths. This project does not make any statements about the quantities of storable energy sources that can be produced.

Biomass imports from other countries with subsequent processing in Germany are conceivable, but many studies, such as the long-term scenarios from [Nitsch et al. 2012], the "Klimaschutzszenario 2050" [Öko-Institut et al. 2015], and studies by the Federal Environment Agency ("Germany in 2050 – a greenhouse gas-neutral country " [UBA 2014], RESCUE [UBA 2019]) assume that substantial biomass imports do not constitute a sustainable strategy due to the limited availability worldwide.

The transportability or transport worthiness of biomass is also discussed. In the German National Renewable Energy Action Plan (NREAP) [NREAP 2010], high energy density and established logistics concepts are cited as the best technical prerequisites for importing liquid bioenergy sources (biodiesel, bioethanol, vegetable oil), solid bioenergy sources and raw materials with high bulk density (pellets, grain and seeds, etc.) and for biomethane (biogas upgraded to natural gas quality) via the natural gas grid. In the DBFZ's "bioenergy scenario" [DBFZ 2010], cereals and woody biomass, with the exception of silage maize, are also considered worthy of international transport. Against this background, the biomasses considered are primarily wood or liquid or gaseous energy sources from biomass that can be considered worthy of transport.

Biogenic waste/residual materials

The possible availability of biogenic waste and residual materials in Germany was examined in detail in the study by ifeu et al. [BioRest 2019].

For the estimation of possible availability in the EU (except Germany), data from the NREAPs were used, as they are an official source at country level and are based on the same categorisation. The compilation of ECN [ECN 2015], partly supplemented by updates, and the new Croatian NREAPs were used as a basis.

International potential availability of residual materials beyond the EU could not be numerically determined from the literature search. However, DBFZ [2010] contains possible technical availabilities of individual residues for the period 2003 to 2007 based on mapped size classes. These are used here as an approximation.

Cultivated biomass

To be able to draw a comparison of the ecological and economic effects of residues, the project looked at a number of supply paths based on cultivated biomass. As the project does not produce any quantity structures and overall scenarios, it cannot be deduced from this that these paths are desirable. The presentation of availabilities refers exclusively to the type of biomass and the possible countries of origin, as this is the basis for the environmental assessment carried out in this study. Indirect effects of biomass supply are not considered. Reasons for the rejection of cultivated biomass for energy use are documented, for example, in [UBA 2014].

Possible availability of cultivated biomass in Germany for energy use was taken from [Fritsche et al. 2004], [Nitsch et al. 2004, Nitsch et al. 2012] and [DBFZ 2010]. For the EUMENA region, potential availability of cultivated biomass was taken from the NREAPs (European Economic Area) and DBFZ [2010] in the same way as for waste and residual materials.

2.2.3 CO_2 sources

The capture of CO_2 from the air is in principle possible everywhere and even mandatory for all potential sites where no alternatives are available. In connection with the production of synthetic energy sources, however, concentrated sources are always discussed – especially from industry and biogas production.

Industry sources

As part of the transition to a greenhouse gas neutral economy, it is expected that concentrated CO_2 point sources in oil refineries, steel and ammonia production, natural gas processing and hydrogen production through steam reforming will be reduced by 2050 because of the switch to low-carbon processes and eventually disappear altogether. This project therefore focuses on cement production as the main source, as its CO_2 emission is difficult or impossible to avoid. Cement production today provides exhausts with relatively high CO_2 concentrations of 15-35%.

The current production of cement was chosen as an indicator for the site selection of the supply paths. Although the future quantities and the type of CO_2 sources available depend very much on the development of the processes used and the overall production, this development is not modelled here. The quantitative availability of carbon at the sites was estimated based on statistical data on current cement production in the EUMENA region at country level. In particular, statistics from industry associations and production statistics were used.

CO_2 from biogas

In addition to industrial CO_2 sources, fermentation processes in combination with subsequent CO_2 capture can also be used as a source of CO_2 in synthesis processes. Based on the total biogas potential of a region, the CO_2 potential is limited by the number and type of biogas upgrading plants and amounts to about 40-45% of the biogas produced. Limiting factors are a minimum plant size of the biogas upgrading plant – and thus the biogas plant for economic reasons and the proximity to the gas grid for methane injection.

For the direct use of carbon from biomass, the possible availability for the purpose of this study was set out in Chapter 2.2.2. This includes biomass that can be used for fermentation, which could thus also provide CO_2 from biogas. However, no quantification has been provided here.

2.2.4 Results of the preliminary location analysis

The availability of renewable electricity from wind and sun, biomass, CO_2 from the cement industry and water varies greatly in the EUMENA region depending on the location. Electricity can also be transported over long distances - in the present project, transport with HVDC transmission lines was considered as an option in the life cycle assessments. However, transporting biomass or CO_2 from the cement industry is economically limited. They were therefore allocated to the respective country in which they are available and were used to explicitly select the location of production facilities.

Photovoltaics can be used to generate electricity throughout the EUMENA region. While in Europe only full load hours of 900 to 1,100 h/a are achieved, the MENA region offers 1,200 to 1,800 h/a. However, in the MENA region this is surpassed by CSP with full-load hours of around 2,200 h/a, rising to over 7,000 h/a with 14h storage and solar multiple 3.0.

For offshore wind, the North Sea coasts of France, UK, Germany and the Baltic Sea coast have been identified as possible sites for electricity production with full load hours of 3,500 to 4,500 h/a. In contrast, onshore wind farms are possible throughout the EUMENA region, with sites near the coast in Europe offering full load hours of 2,500 to 2,900 h/a, while slightly lower full load hours of 2,100 to 2,400 h/a occur in MENA.

At the particularly favourable locations

- synthetic fuels can be produced directly (e.g., based on CO_2 from the air), whereby in MENA, in principle, water desalination must be added to the supply chain;
- or electricity generated and transferred to the carbon source.

In the second case, due to the possible availability of wood biomass (forest residues, wood scraps, industrial residues) within the EU, France, Italy, Finland and Sweden are the main potential production sites. In addition, Turkey, Ukraine and Egypt have relevant quantities of straw. Other options for cultivated biomass are France, Italy and possibly Spain within the EU and Ukraine outside the EU. Fermentable residues are available mainly in Italy, France, the UK and Spain, and outside the EU in Turkey (municipal waste). From these, relevant quantities of CO_2 from biogas upgrading could also be extracted and used as a carbon source.

CO_2 emissions from the cement industry are available in many countries of the EUMENA region. In Europe, particularly large quantities of CO_2 from cement are currently being produced in Turkey, but also in Germany and Italy. In the Middle East, Iran, Saudi Arabia and the United Arab Emirates have large production volumes, while in North Africa, relevant CO_2 quantities are produced mainly in Egypt and Algeria.

In all countries in the EUMENA region, supply paths can be established to capture CO_2 from the air.

2.3 Life cycle assessments

In this part of the study, a quantitative or qualitative analysis and evaluation of the selected supply paths from an environmental and resource perspective was carried out. Since a critical appraisal of the results is not provided for in the project's terms of reference, this study does not fulfil all the requirements of the ISO standards for life cycle assessments ISO 14040 and ISO 14044. In principle, however, the methodology is closely oriented to these standards.

Functional unit

The functional unit has been set at 1 MJ (lower calorific value) energy source. Energy sources in the context of this study are: hydrogen, Fischer-Tropsch fuel, methanol, synthetic natural gas, biomethane and the fossil reference products diesel, petrol, methanol, natural gas and hydrogen from natural gas.

Geographical scope

In Germany, the energy sources are provided "free filling station" or "free gas connection" to a central end point in the middle of Germany. Depending on the supply path, energy production, electrolysis, biomass cultivation and processing, CO_2 supply and hydrocarbon synthesis take place in Germany or in countries in the EUMENA region.

Time scope

Three different time periods were considered: The electricity situation based on the year 2015, a medium-term future development defined as "year 2030" and a longer-term development defined as "year 2050". For the present situation, data describing the electricity state of the art were used, while the situation in 2030 and 2050 was estimated using models for the development of electrolysis and synthesis technologies and the general industrial landscape. Details of the models used can be found in Chapter 2.3.1.

System boundaries

For this study, all processes along the processing chain from raw material extraction to the provision of the product (FT fuel, methanol, synthetic natural gas, biogas, hydrogen) in Germany were considered. Subsequent conversion processes, especially the utilisation phase, are located outside the system under study.

The system under consideration includes the following processes for the provision of the products:

- Provision of electrical energy including transmission losses
- Provision of thermal energy
- Cultivation/collection and transport of biomass
- Operation of plants for H_2 electrolysis, CO_2 capture, biomass treatment (drying, pelletisation), product synthesis and preparation, if necessary.
- Extraction and transport of fossil fuels for electricity and/or heat production
- Infrastructure and operating materials (catalysts, electrolytes, washing solutions) for plants and means of transport, in particular for the provision of renewable energy, electrolysers and synthesis plants
- Upstream of all materials used in the above-mentioned processes
- Release of the CO_2 bound in the energy source at the end of life

- Not included in the system boundaries mentioned here are the emissions and waste produced at the end of the product's life - with the exception of the carbon bound in the product as CO_2.

The associated individual processes or modules were parameterised in the life cycle assessment and material flow software Umberto and linked in models.

2.3.1 Infrastructure and background system

During the transformation to a largely greenhouse gas neutral economic system, which is expected to be almost completed in Germany by 2050, the environmental impacts of the processes under consideration are changing. Electricity generation will gradually be switched to renewable sources, recycling rates in the production of iron, steel and other metals will increase, fossil raw materials and fuels in industry and transport will be replaced by those with a smaller carbon footprint. Energy efficiency is increasing in all sectors of the economy.

To estimate how the changes in this so-called background system affect the environmental impacts of the manufacture of the products under consideration, numerous processes in the models of the life cycle assessment and material flow software Umberto were adapted for the calculations for the support years 2030 and 2050. Data for the changes on the transformation path were taken from the parallel study "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE" [UBA 2019].

In particular, the following processes were modelled in this study according to the "GreenEe1" green scenario of the UBA RESCUE study:

- Electricity generation (with share of renewable energies (incl. PtG with conversion into electricity): 2030: 75%, 2050: 100%),
- Steel production (increasing recycling rates, conversion to hydrogen as a reducing agent in the DRI (direct reduced iron) process),
- Cement production (firing with methane from PtG production, reduction of the clinker factor, novel binders)
- Aluminium and copper production (increasing recycling rates, conversion to inert anodes)
- Production of plastics (covering the demand for raw materials and process heat by regeneratively produced methane)

For the energy systems and production processes within the EU, the same transformation path as in Germany was assumed, for the rest of the world a development with a ten-year delay.

2.3.2 General assumptions within the supply paths

Energy Management

Most of the synthesis processes under consideration are exothermic - heat is released during the manufacture of the products. This heat can be used for various other process steps (e.g., CO_2 capture, biomass upgrading, high-temperature electrolysis) or it can be used to generate electricity. Within the scope of this study, heat utilisation for CO_2 capture and biomass conditioning was given priority over utilisation in high-temperature electrolysis.

Full load hours

The modular structure of the supply paths makes it possible, among other things, to identify the influence of different power generation options with their respective production loads and full-load hours. However, future plants will most likely operate with a mix of renewable electricity sources or even temporarily with the general electricity mix. On the other hand, it is also conceivable that the plants will only be operated when there is a surplus of renewable electricity (grid-supportive).

These cases could not all be represented in this study. In order to define the range of operating modes, the ecological and economic calculations in this project were carried out in two main variants:

1. Operating mode "full load hours synthesis plant": The electrolysers, CO_2 capture and synthesis plants run during the technically maximum possible annual operating hours (usually around 8,000). In mathematical terms they are, nevertheless, supplied from the assigned power source. The storage facilities required for this (electricity, H_2, CO_2) are neglected.
2. Operating mode "full load hours power source": The electrolysers, CO_2 capture and synthesis plants only run during the operating hours corresponding to the full load hours of the assigned power source.
   Example: PV plants in Morocco average 1729 full-load hours per year. Irrespective of the course of the day, the synthesis plants are only operated for this time each year. Possible technical consequences of intermittent operation (catalyst ageing, efficiency of start-up processes) are neglected.

For the products Fischer-Tropsch fuel, methanol and synthetic natural gas, supply paths were also calculated using the respective electricity mix of the support years.

Transport

Some simplifying assumptions have been made for the transport of the products or CO_2:

- CO_2 is not transported. The synthesis plants are either built near the CO_2 sources or the CO_2 is captured from the air
- Hydrogen is not transported to P(B)tL plants but produced on site by electrolysis. Hydrogen as a product is fed into the existing gas grid.
- Trucks used to transport the products will still run on fossil fuels in 2015 and 2030, and on Fischer-Tropsch fuel in 2050.
- Ships used to transport the products will still be powered by fossil fuels in 2015 and 2030, and in 2050 by the respective product generated in the supply path.
- The end of all supply paths is a single final destination at the centre of Germany, i.e., an average transport distance by truck or gas grid is assumed within Germany. Storage of the products at this fictitious destination is not taken into account.

Allocations

The handling of by-products or the evaluation of the use of secondary raw materials requires some methodological decisions: How are the expenditures (raw material and material input on the input side and emissions and waste on the output side) allocated to the products of a process? This is regulated by so-called allocations. Since there is no scientifically justified unambiguous allocation method, specifications are required which must be analysed for possible violations of basic scientific laws (above all consistency of the mass and energy balance).

The following principles apply to the allocation rules set out in this study:

- For processes with more than one valuable product, physical allocations according to energy (lower calorific value) or exergy content are used where possible. Heat energy and electrical energy are also considered as valuable products, which are then allocated according to their exergy content.

- The use of a by-product within the supply path ("closed loop"), such as the application of fermentation residues from biogas production to fertilise the cultivated biomass, is taken into account in the balance sheet. The same applies to thermal and electrical energy from the synthesis processes: this replaces the corresponding energy in upstream processes such as electrolysis or CO_2 capture. Beyond this, no credits or burdens (e.g., for fermentation residues from the fermentation of biogenic residues and waste materials) are allocated.
- Some assumptions had to be made for the supply of CO_2 to produce synthetic hydrocarbons:
  - CO_2 emissions from a process aimed at producing a valuable product (e.g., cement production or power generation in a power plant) are understood as "waste for recycling". All loads of the upstream chain (provision of raw materials, transport, pre-processes) and the main process itself are assigned to the respective value product.
    In particular, the burden of carbon from fossil sources is not allocated to the PtX product. However, the global warming potential resulting from these carbon quantities is shown for information purposes.
  - In processes in which CO_2 does not have to be captured from the product mixture of the emitting process anyway (e.g., flue gases, cement plant, direct air capture), the expenses for separating the CO_2 from the process waste gas or the air as well as all subsequent treatment steps (cleaning, compression, ...) are charged to the CO_2 and thus to the product generated from it.
  - A special case is the use of CO_2 from a lignite-fired power plant with an oxyfuel process. This study assumes that the oxyfuel process is primarily used in a power plant to capture CO_2 and store it geologically in the long term (CCS, carbon capture and storage). The use of a subset to produce PtX energy carriers thus means a release into the atmosphere that would not occur without this use. The CO_2 is therefore completely charged to the PtX energy source.
  - Another special case is the use of CO_2 from biogas upgrading. In the processing of biomethane, the CO_2 is separated from the raw biogas and released into the atmosphere, which means it is waste. On the other hand, direct energetic use of the biogas is also common today. A separation of the CO_2 would therefore be an additional effort.
    Therefore, in this case, an allocation of the expenses for the separation of the CO_2 according to the mass ratio (CH_4/CO_2) was determined as a middle course.

2.3.3 Impact categories and indicators

To be able to assess the environmental impact of a process chain, environmental impact categories are used in life cycle assessments as far as possible. The individual pollutants are combined into a single so-called impact indicator using characterisation factors. In addition, indicators for the use of energy and raw material resources are used.

The following impact categories and indicators were selected:

- Climate change: Global Warming Potential (GWP 100a) according to [IPCC 2013]in kg CO_2eq.
- Resource use: Cumulative energy demand (CED) in MJ (LHV)
- Acidification: Acidification Potential (AP) according to [Hauschild / Wenzel 1998]in g SO_2eq.

- Summer smog: Photochemical Ozone Creation Potential (POCP) according to ReCiPe [Goedekoop et al. 2009]in g C_2H_4eq.
- Eutrophication: Eutrophication potential (EP) according to [Heijungs et al. 1992]in g PO_4eq.
- Ozone depletion: Ozone depletion potential (ODP) according to [WMO 2014]in g CFC-11eq.
- Fine dust: Particulate Matter < 10 µm (PM_{10}) according to De [De Leeuw 2002; WHO 2006]g PM_{10}eq.
- Cumulated raw material demand (CRD)
- Use of natural areas: Hemeroby concept according to Fehrenbach et al. [2015] in m^2a
- Water consumption: Net water consumption (input minus output to the same water catchment area) in l H_2O

2.4 Selection of supply paths

From the technology modules defined at the beginning of the project, a limited basic set of paths had to be defined that were technically feasible and plausible in terms of the basic availability of electricity, carbon, and water. The selection should be independent of political or economic conditions - even if there are doubts about sustainably available biomass resources, e.g., However, there are many ways of combining the modules in such a way that supply paths are created which have a technical implementation potential and locations with significant availability.

The second criterion was that the set of selected paths should include both, those with particularly low environmental impacts and disadvantageous paths with particularly high environmental impacts. In view of the numerous process steps and their different characteristics, however, it is not easy to clarify which variants (e.g., of the power source, the electrolysis technology, the synthesis or transport route) in a supply path have a major and which only a minor impact on the environmental impact. Selection based on expert estimates alone is not sufficient to eliminate this uncertainty.

2.4.1 Screening life cycle assessments

To identify a meaningful selection of paths that are particularly favourable or unfavourable from an environmental point of view, so-called screening LCAs were drawn up. These balances were carried out in two steps. In the first step, the technologies were grouped with regard to the process steps in the supply path (power generation, CO_2 source, synthesis) and analysed for their global warming potential (GWP) using the method of life cycle assessment. In many studies, the GWP has proven to be a good leading indicator for many other environmental impacts. The reduction of greenhouse gas emissions is also one of the primary reasons for producing electricity and biomass-based energy carriers.

Table 2: Grouping of the technology modules according to process steps

Electricity	Electrolysis	CO_2	Biomass BtL	Biomass Gas	Synthesis
WindOn	AEL	DAC (air)	Straw	Maize	PBtL
WindOff	PEM	Biogas	Forest residue wood	Slurry	BtL
Water	HTEL	Flue gas	SRC	Bio-waste	PtL
CSP		Cement	Miscanthus	Grass silage	PtG

Electricity	Electrolysis	CO_2	Biomass BtL	Biomass Gas	Synthesis
PVground			Wood scraps		biomethane
PVroof					
Geother-mal energy					

WindON/OFF: Wind energy plants onshore/offshore, Water: Run-of-river power plants, CSP: Concentrating solar power plants, PVground/roof: Photovoltaic plants open space/roof, AEL: Alkaline electrolysis, PEM: PEM electrolysis, HTEL: high-temperature electrolysis, DAC: CO_2 capture from the air, SRC: Short-rotation coppice (poplars), BtL: Synthesis based on biomass, PBtL: Synthesis based on electricity and biomass, PtL: Synthesis based on electricity, PtG: Synthesis synthetic natural gas based on electricity
Light green: Process steps with lowest GWP within the group
Light brown: Process steps with highest GWP within the group

Table 2 shows the technology groups and the results of the LCA GWP analyses with colour-coded background. Among the electricity generation options, hydropower plants have the lowest global warming potential per kilowatt-hour, and ground-mounted PV systems the highest. Due to the high energy demand, CO_2 capture from the air has a higher GWP than capture from biogas. Among the biomass sources for BtL synthesis, straw performs best and wood from short-rotation plantations worst. For biomass fermentation, maize brings the highest GHG loads, waste such as biowaste the lowest.

In a second step, the modules with the highest and lowest global warming potential were combined to form supply paths. These paths thus define a corridor between paths with particularly low and particularly high global warming potential. For each of these paths, the global warming potential was then calculated using the technology data for 2015 and without including specific location factors, namely for the PtL paths with Fischer-Tropsch and methanol synthesis, respectively. These calculations made it possible to identify those process steps that made particularly high or low contributions to the overall result.

2.4.2 List of selected supply paths

Based on the findings of the screening life cycle assessments and in connection with the analysis of location factors in Chapter 2.2 a total of 62 supply paths were selected according to the following considerations

- The paths of the screening LCAs were already selected to include both particularly favourable and particularly unfavourable overall results. Therefore, it made sense to consider them also in the full LCA calculation. However, instead of electricity from hydropower, most of these paths were calculated using wind power, as this is a source with greater potential in Germany and other locations.
- The provision of electricity for electrolysis is the decisive environmental factor for many processes. It therefore made sense to consider several other types of generation and locations. In Germany these were additionally wind onshore and offshore, abroad wind onshore, CSP, and geothermal energy.

- To examine the impact of transporting electricity or products from abroad, supply paths were selected using the examples of Morocco and Saudi Arabia, each with transport by HVDC transmission/tanker/pipeline.
- To explore the potential of new electrolysis techniques, high-temperature electrolysis in combination with two FT-P(B)tL processes and PEM electrolysis in the best PtL path were selected as paths.
- CO_2 sources in industry and power plants should also be included to identify options and risks in this area. Therefore, cement plants and lignite-fired power plants were selected as CO_2 sources for some of the paths. For Fischer-Tropsch fuel, methanol and SNG, one path of each should be considered with electricity from the German electricity mix.
- In addition, the cases of CO_2 capture from a waste incineration plant and an oxyfuel power plant for Fischer-Tropsch fuels will be considered.
- For biomethane, two additional paths with alternative purification/separation processes have been added.

The criteria for this selection are once again presented in key points in Table 3.

Table 3: Selection criteria for the final supply paths

Selection criterion	Path elements
Paths from the overview life cycle assessment were retained, hydropower replaced by wind power	Straw and SRC as BtL biomass, organic waste/green cuttings and maize/manure as biogas substrates, CO_2 from DAC and biogas processing, PVground and wind onshore as power source, AEL
Other variations in electricity generation	Offshore wind, CSP, geothermal energy, electricity mix
Locations abroad, transport by HVDC/tanker/pipeline	Morocco, Saudi Arabia, Iceland
Variations of electrolysis technologies	PEM, HTEL
Other sources of CO_2	Cement industry, lignite power plant, oxyfuel power plant, waste incineration plant
Variation of biogas/biomethane treatment process	Amine scrubbinging, pressurised water washing, membrane separation

All supply paths are shown in Table 4 to Table 9 The fact that the tables contain for a relatively large number of paths with Germany as the production location does not mean that this location should be given preference over production abroad. Rather, this is a simplification that allows the influence of supply factors beyond transport and full load hours of the power source to be examined. The latter influences are considered and examined in several foreign paths and can be transferred to other - not examined - supply paths.

Table 4: Fischer-Tropsch fuel supply paths

Path No.	Location	Synthesis	CO_2 source	Biomass	Electricity	H_2	Transport
1.	Germany	BtL		Straw			Truck
2.	Germany	PBtL		Straw	WindON	AEL	Truck
3.	Germany	PtL	Biogas		WindON	AEL	Truck
4.	Germany	PtL	Cement		PVground	AEL	Truck
5.	Saudi Arabia	PtL (in Germany)	Cement		PVground	AEL	HVDC + truck
6.	Saudi Arabia	PtL	Cement		PVground	AEL	Tanker + truck
7.	Saudi Arabia	PtL	Cement		CSP	AEL	Tanker + truck
8.	Germany	BtL		SRC			Truck
9.	Germany	PBtL		SRC	PVground	AEL	Truck
10.	Germany	PtL	DAC		PVground	AEL	Truck
11.	Germany	PtL	DAC		WindOFF	AEL	Truck
12.	Morocco	PtL	DAC		CSP	AEL	Tanker + truck
13.	Morocco	PtL	DAC		WindON	AEL	Tanker + truck
14.	Morocco	PtL	DAC		PVground	AEL	Tanker + truck
15.	Iceland	PtL	Geothermal energy		Geothermal energy	AEL	Tanker + truck
16.	Sweden	PBtL		Forest residue wood	Water	AEL	Tanker + truck
17.	Sweden	PBtL		SRC	Water	AEL	Tanker + truck
18.	Germany	PBtL		SRC	WindOFF	HTEL	Truck
19.	Germany	PtL	DAC		WindOFF	HTEL	Truck
20.	Germany	PtL	Biogas		WindON	PEM	Truck
21.	Germany	PtL	Lignite power plant		WindON	AEL	Truck
22.	Germany	PtL	Lignite power plant		Grid electric-ity mix	AEL	Truck

Table 5: Methanol supply paths

Path No.	Location	Synthesis	CO_2 source	Biomass	Electricity	H_2	Transport
23.	Germany	BtL		Straw			Truck
24.	Germany	PBtL		Straw	WindON	AEL	Truck
25.	Germany	PtL	Biogas		WindON	AEL	Truck
26.	Germany	PtL	Cement		PVground	AEL	Truck
27.	Saudi Arabia (Electricity)	PtL (in Germany)	Cement		PVground	AEL	HVDC + Truck
28.	Saudi Arabia	PtL	Cement		PVground	AEL	Tanker + truck
29.	Saudi Arabia	PtL	Cement		CSP	AEL	Tanker + truck
30.	Germany	BtL		SRC			Truck
31.	Germany	PBtL		SRC	PVground	AEL	Truck
32.	Germany	PtL	DAC		PVground	AEL	Truck
33.	Germany	PtL	DAC		WindOFF	AEL	Truck
34.	Morocco	PtL	DAC		CSP	AEL	Tanker + truck
35.	Morocco	PtL	DAC		WindON	AEL	Tanker + truck
36.	Morocco	PtL	DAC		PVground	AEL	Tanker + truck
37.	Iceland	PtL	Geothermal energy		Geothermal energy	AEL	Tanker + truck
38.	Sweden	PBtL		Forest residue wood	Water	AEL	Tanker + truck
39.	Sweden	PBtL		SRC	Water	AEL	Tanker + truck
40.	Germany	PtL	Biogas		WindON	PEM	Truck
41.	Germany	PtL	Lignite power plant		WindON	AEL	Truck
42.	Germany	PtL	Lignite power plant		Grid electricity mix	AEL	Truck

Table 6: Supply path for synthetic natural gas

Path No.	Location	Synthesis	CO_2 source	Electricity	H_2	Transport
43.	Germany	PtG	Biogas	WindON	AEL	Gas grid (Germany)
44.	Germany	PtG	Cement	PVground	AEL	Gas grid (Germany)
45.	Saudi Arabia (electricity)	PtL (in Germany)	Cement	PVground	AEL	HVDC + gas grid
46.	Saudi Arabia	PtG	Cement	PVground	AEL	Pipeline
47.	Saudi Arabia	PtG	Cement	PVground	AEL	Tanker + gas grid
48.	Germany	PtG	DAC	PVground	AEL	Gas grid (Germany)
49.	Germany	PtG	DAC	WindOFF	AEL	Gas grid (Germany)
50.	Morocco (electricity)	PtG (in Germany)	DAC	CSP	AEL	HVDC + gas grid
51.	Morocco	PtG	DAC	CSP	AEL	Pipeline
52.	Morocco	PtG	DAC	CSP	AEL	Tanker + gas grid
53.	Germany	PtG	Lignite power plant	WindON	AEL	Gas grid (Germany)
54.	Germany	PtG	Lignite power plant	Grid electricity mix	AEL	Gas grid (Germany)

Table 7: Supply paths for hydrogen

Path No.	Location	Synthesis	Electricity	H_2	Transport
55.	Germany	H_2	WindON	AEL	Gas grid (Germany)
56.	Germany	H_2	WindON	PEM	Gas grid (Germany)

Table 8: Supply paths for biomethane

Path No.	Loca-tion	Synthesis	Biomass (gas)	separation technology	Transport
57.	Ger-many	Fermentation	Organic waste/green cuttings	Amine scrubbing	Gas grid (Germany)
58.	Ger-many	Fermentation	Maize/slurry	Amine scrubbing	Gas grid (Germany)
59.	Ger-many	Fermentation	Organic waste/green cuttings	Pressure water scrubbing	Gas grid (Germany)
60.	Ger-many	Fermentation	Organic waste/green cuttings	Membrane separation	Gas grid (Germany)

Table 9: Additional supply paths for Fischer-Tropsch fuel

Path No.	Location	Synthesis	CO_2 source	Electricity	H_2	Transport
61.	Ger-many	PtL	Flue gas oxyfuel lignite-fired power plant	WindON	AEL	Truck
62.	Ger-many	PtL	Flue gas waste incineration plant	WindON	AEL	Truck

3 Results of the life cycle assessments

The results of the LCA calculations are very comprehensive and can only be presented here as an overview. In Chapter 5 of the annex to this report, the results are analysed in detail both at product level and across products. A presentation of the results for the support year 2030 is omitted altogether, as this does not allow any additional findings to be expected as an intermediate step between the years 2015 and 2050.

The environmental impacts of the supply paths of different products (Fischer-Tropsch fuel, methanol, SNG, biomethane and hydrogen) can be compared by reference to their energy content. However, the comparisons made in this way are limited in their informative value, as

- the products have different areas and purposes of use (as fuel, combustible, chemical base material, reducing agent in industry) and
- the use phase of the products is not included in this study, although it contributes to the overall environmental burden of the energy sources. Environmental impacts resulting from incineration, which differ from product to product are therefore not included in the comparisons here. An exception is the global warming potential, which also includes the use phase via the stoichiometric emission factors (CO_2 release when completely incinerated).

Chapter 3.1provides examples of the global warming potential, showing how the environmental impacts differ for different products, types of synthesis, operating modes and support years.

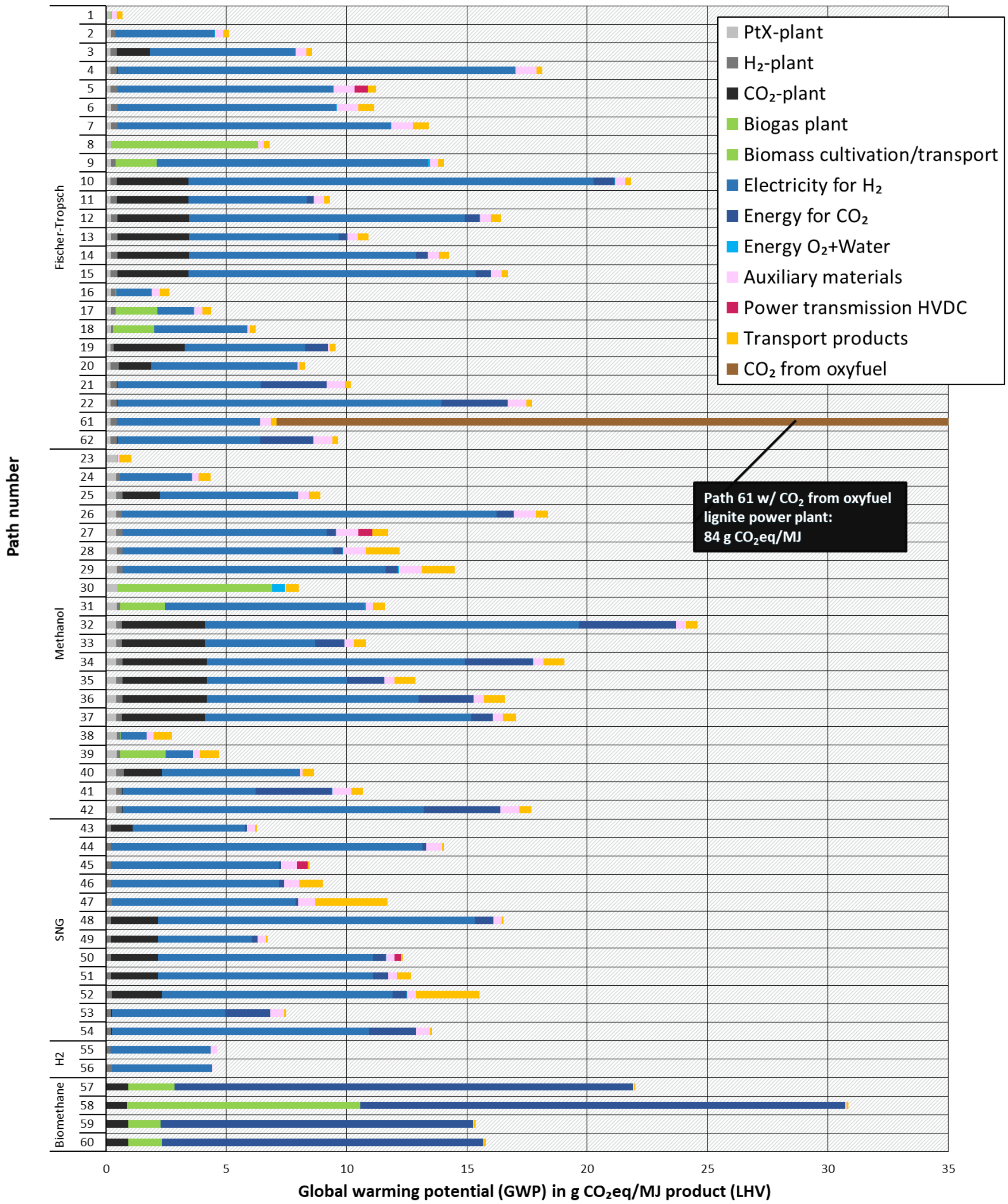
In Chapter 3.2a dominance analysis identifies the contributions of the individual production steps of the supply path (e.g., electricity generation, construction and operation of synthesis plants, transport of electricity, biomass and products) to all environmental impacts for the year 2050. In addition, it is analysed which materials (e.g., steel, cement, aluminium, copper) are responsible for environmental impacts in 2050 via their production processes.

Chapter 3.3then shows how the supply paths in the individual impact categories can be normalised by comparing them with electricity emissions and demand in Germany.

3.1 Global warming potential 2015 and 2050

A central question is first what climate impact synthetic energy sources have and whether they provide relief compared with fossil reference products. Figure 2 shows the results for all supply paths in 2050 (in the "full-load hours synthesis plant" mode of operation). The global warming potential based on energy content ranges from 0.69 g CO_2eq/MJ for path 1 (Fischer-Tropsch fuel, BtL synthesis in Germany with straw as a residual material) to 84 g CO_2eq/MJ for path 61 (Fischer-Tropsch fuel, PtL synthesis, CO_2 capture from an oxyfuel power plant, wind power as a power source for electrolysis).

Figure 2 **Global warming potential of all supply paths in 2050 (full-load hours of synthesis plant)**



Source: own figure, ifeu

Compared to the fossil reference values in Table 10 many paths are about 85-90% lower. A few paths also achieve a reduction of 95% compared to their fossil reference. As analysed in chapter 3.2 below, the fact that the values are not even lower despite the use of renewable energies is mainly due to the production loads of the electricity generation plants. For this study it was assumed that the world outside Europe is also undergoing a transformation towards greenhouse gas neutrality, but with a delay of ten years. Only if renewable energy sources were fully used along the entire production chain these greenhouse gas emissions could also be largely avoided

– but a residual amount of non-carbon dioxide greenhouse gas emissions, such as methane and nitrous oxide, will probably remain.

Table 10: Conventional reference products and their global warming potential including upstream chains

Environmental Impact	Diesel	Petrol	Methanol from natural gas	Natural gas	Hydrogen from natural gas
Global warming potential g CO_2eq/MJ	90	87	95	63	88

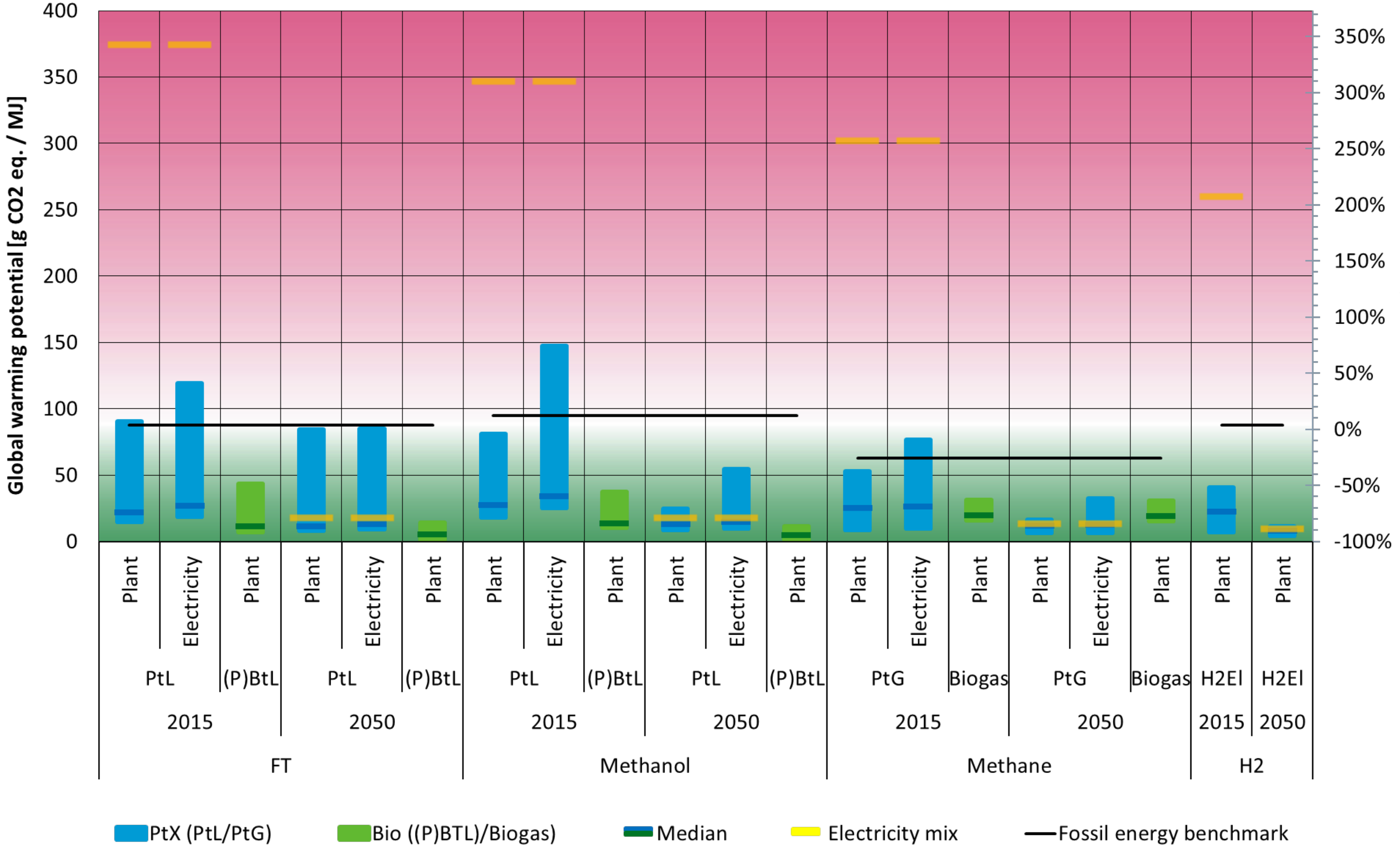
In addition to the global warming potential in 2050, today's GHG emissions of the supply paths are also relevant: Because the background system changes only slowly, the global warming potential will remain closer for many years to today's levels than to 2050 levels.

Figure 3 shows the bandwidths of the global warming potential in terms of energy content for all products, different groups of supply paths, the support years 2015 and 2050 and the two modes of operation. The global warming potentials of the paths in which the electricity mix is used are marked separately. In addition, the discharge or pollution compared to an average fossil reference (average value from petrol/diesel, methanol, natural gas, hydrogen from natural gas) is shown on the right-hand axis. In addition, the background of the graph is coloured red (additional load) and green (additional relief) to allow for quick classification of the results.

The terms "plant" and "electricity" designate the mode of operation of the synthesis plant - according to possible full load hours of the plant or the electricity generation for electrolysis (Chapter 2.3.2). Put simply, in the operating mode "full load hours power source", the environmental impacts of the construction of electrolysers, synthesis and deposition plants increase, since these impacts are distributed over the respective fixed lifetimes to the energy carrier quantities produced during this time. If the plants run for shorter periods of time each year, fewer energy sources are produced, which then receive a larger "backpack" of environmental impacts per unit from the construction of the plant. For predominantly biomass-based (P)BtL processes, operation at the full load hours of the power source is not to be expected and is therefore not shown in figures.

The supply paths for liquid energy sources are grouped into fully electricity-based PtL paths and predominantly biomass-based (P)BtL paths. The reasons for this are that (P)BtL processes have a lower degree of technological maturity. For each product group, the median of all results of this group is also shown.

Figure 3: Global warming potential - 2015 and 2050 ranges and potential reduction/increase of burdens compared to fossil reference



Source: own figure, ifeu

In the overall picture, the bandwidths reach up to 95% below the fossil reference. However, especially for 2015, there are also paths for all energy sources that perform worse than the reference and thus place an additional burden on the global warming potential. This applies in particular to the operation of the plants with electricity from the electricity mix, which still has a very poor greenhouse gas balance in 2015. In this case, the production of synthetic energy sources has a global warming potential of around 200-350% of the fossil reference product.

In 2015, **fully electricity-based** PtL energy sources (FT fuels and methanol) show similar ranges of results, while electricity-based methane (SNG) performs better. The hydrogen paths show the smallest spread of results and the largest gap to the global warming potential of the reference product.

The main sources of global warming potential for all electricity-based products are primarily the electricity used for electrolysis. In the case of paths with CO_2 capture from the air, the construction of the capture plants can also make a significant contribution (in extreme cases up to 30%).

The predominantly **biomass-based** liquid energy sources (FT fuel and methanol from (P)BtL syntheses) will perform better in 2015 than the fully electricity-based ones - both in terms of the respective maximum and minimum values of the bandwidths of the supply paths. The results are different for methane. Here the most favourable PtG paths have a lower global warming potential than the most favourable biogas paths. In a comparison of the least favourable paths, biomethane is clearly below the fossil reference than electricity-based methane. For all predominantly biomass-based products, the main sources of the global warming potential are the cultivation and transport of biomass and, in the PBtL paths, also the electricity for electrolysis.

In 2050, results will improve for almost all products and modes of operation. This is mainly due to the decreasing greenhouse intensity of electricity for electrolysis. The materials used in the construction of the electricity generation, synthesis and separation plants (steel, concrete, aluminium, copper) are responsible for lower emissions due to changed production processes and the largely defossilised energy system (Chapter 2.3.1). In addition, the use of synthetic energy sources reduces greenhouse gas emissions from the transport of products. For FT fuel, the global warming potential of the least favourable path (path 61) decreases less strongly, since in this path the CO_2 from a lignite-oxyfuel power plant is attributed entirely to FT fuel (Chapter 2.3.2).

Averaged over all supply paths, CO_2 contributes 76%, CH_4 12% and N_2O 10% to the global warming potential in 2050.

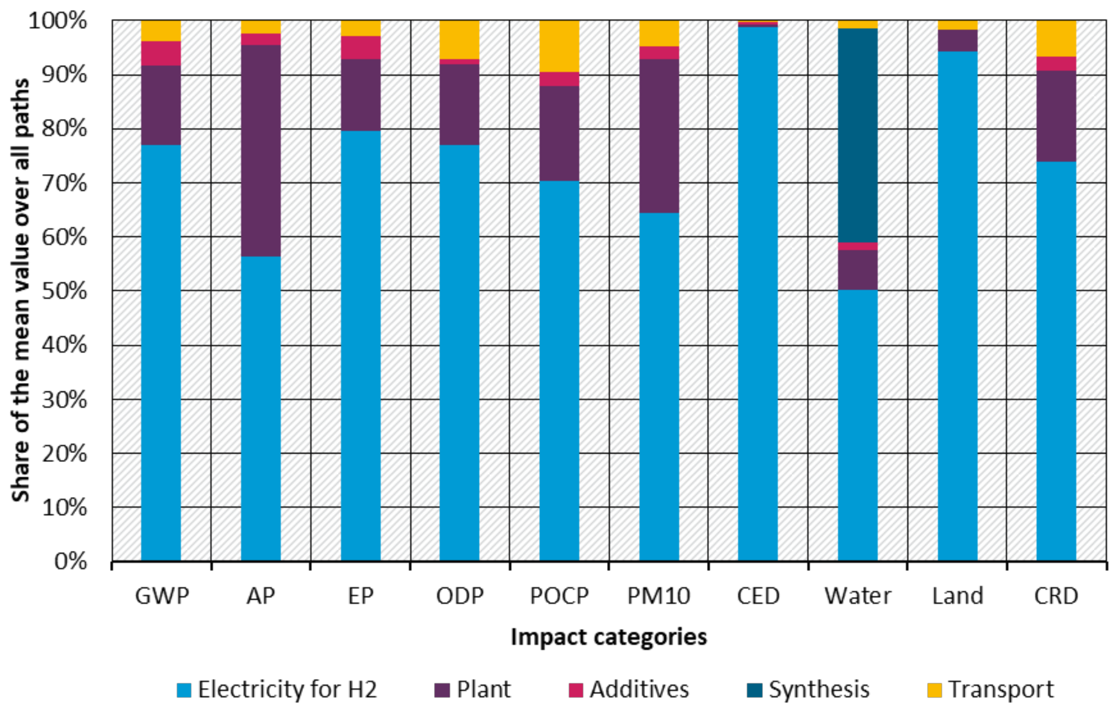
In order to keep the global warming potential of the energy sources as low as possible, the plants should not be operated with electricity from the general mix in 2015 and 2030. Either the plants should then only run in the "full load hours power source" mode of operation, or storage facilities for hydrogen/CO_2/electricity must be added to the plant. Both options increase emissions and costs. The use of storage facilities was not modelled in this study.

In 2050 the difference between the two modes of operation will be less significant. In terms of global warming potential, it will then be easy to use the general electricity mix.

3.2 Dominance analysis - processes and materials

The dominance analysis examined how the individual process steps contribute to the various environmental impacts. For all ten impact categories studied, Figure 4 shows the (median) shares for 2050 averaged over all **fully electricity-based** supply paths – i.e., for all supply paths in which no biomass is used.

Figure 4: Dominance analysis of all environmental impact categories for the medians over all fully electricity-based supply paths in 2050 (full-load hours synthesis plant)

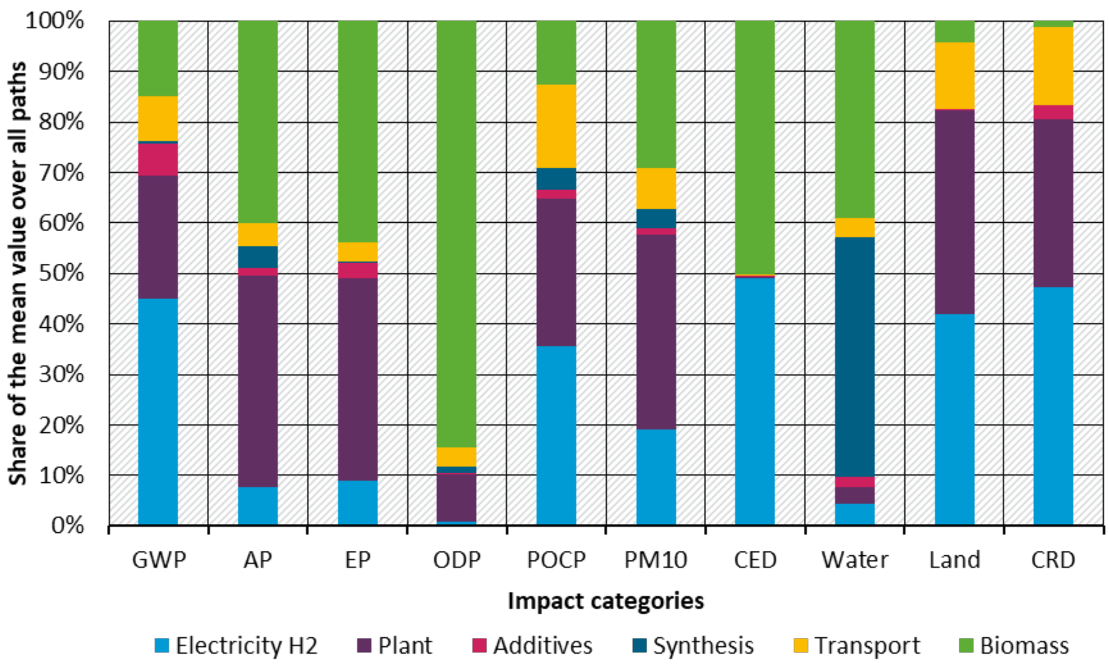


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

It is shown that in 2050 the generation of electricity for electrolysis and the construction of synthesis and separation plants contribute to almost 90% in most impact categories. The exception is water consumption, where the direct process water demand contributes about one third, averaged over all fully electricity-based paths. To a lesser extent, transport infrastructure (pipelines, ships, trucks, etc.) and direct emissions from transport contribute across all impact categories.

Figure 5: Dominance analysis of all environmental impact categories for the medians over all biomass-based supply paths in 2050 (full-load hours synthesis plant)



GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

Figure 5 shows the dominance analysis for all impact categories – averaged over all supply paths in which **biogenic residues and cultivated biomass** are used – for the year 2050. The use of electricity for electrolysis in the (P)BtL paths also leads to considerable contributions here. However, biomass also makes a major contribution to the environmental impacts. Both the production and use of mineral fertilisers and the direct emissions from the synthesis of the energy sources (biomass gasification) make relevant contributions to acidification, ozone depletion and photochemical ozone creation potential as well as secondary particulate matter formation.

In the dominant process steps identified by the analysis, there is a relatively small number of materials and processes for both the fully electricity-based and the biomass-based supply paths, which are the main cause of the environmental impacts:

- Production and operation of electricity generation facilities:
  - For wind turbines, the most important materials are steel and glass fibre reinforced plastics (GRP); also relevant are the production of aluminium, copper and cement as well as transport for plant construction.
  - For photovoltaic systems, the production of copper and aluminium dominates. To a lesser extent, the production of silver, glass and steel also plays a role.
  - Electricity generation from geothermal energy in Iceland is associated with very high H_2S emissions.

- Concentrating solar power (CSP) plants with liquid salt heat storage use nitrate salts as storage medium, which cause significant N_2O emissions during production.

- Installations (electrolysers, synthesis plants, CO_2 capture plants):
  - Here, too, the production of a few materials used in the construction of the plants makes a dominant contribution to the environmental impacts: The largest contribution is made by steel, followed by aluminium, copper and cement.
  - Direct emissions from synthesis plants only contribute to some environmental impacts to a relevant extent in (P)BtL processes with biomass gasification (e.g., to acidification and summer smog potential)
- The production of steel, aluminium and copper also plays a dominant role in the transport of electricity and PtX energy sources – especially for the construction of trucks, ships and pipelines. Added to this are the direct emissions from the combustion of the fuels in the engines of the means of transport.
- In the environmental categories where biomass makes a relevant contribution, the production of nitrogen fertiliser for cultivated biomass and direct emissions from fertiliser application, in particular NH_3, N_2O and nitrate, contribute most. In addition, there are the direct emissions from the transport of the biomass.

3.3 Normalisation

Chapter 3.1 showed that the production of synthetic energy sources is usually associated with a lower global warming potential than that of fossil reference products. In many other impact categories, however, synthetic energy sources perform significantly worse than the reference.

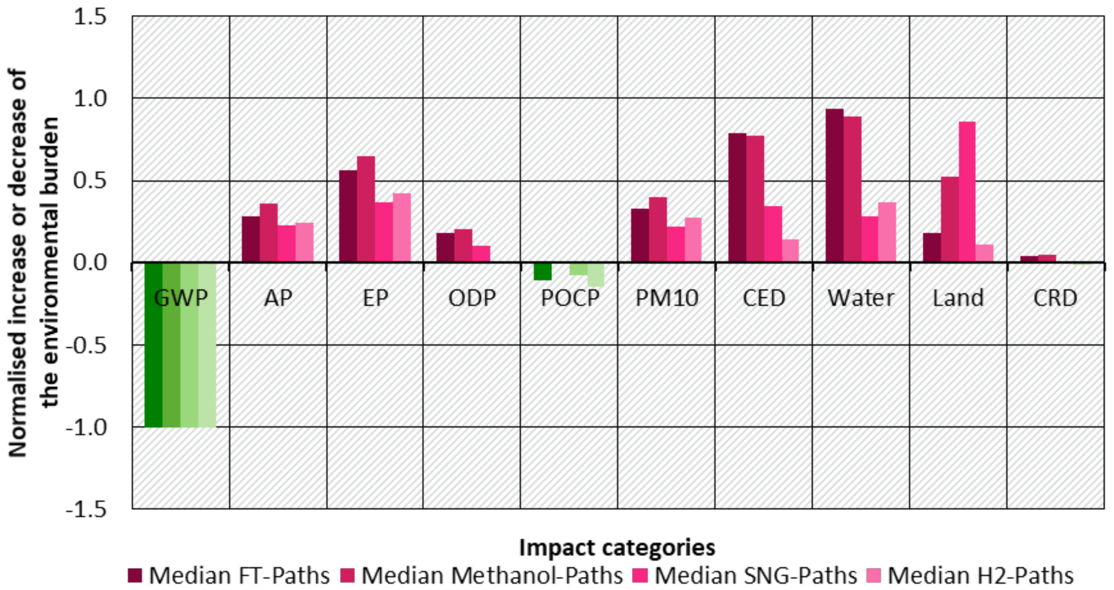
In order to estimate how relevant the additional burdens and reliefs are, the magnitude of the additional environmental impacts is related to electricity environmental burdens. This evaluation step in life cycle assessments is known as standardisation, see e.g., [UBA 1999].

In this study, the starting point for standardisation is the calculated additional burden or relief that would result if a fossil fuel were replaced by a synthetic energy source in 2050. An arithmetic mean value for the environmental impacts of fossil petrol, diesel, natural gas and hydrogen was calculated as the fossil reference to be replaced. These values were compared with the environmental impacts that would result from the production of a synthetic energy carrier that covers the same energy demand. The difference quantifies the calculated additional specific burden or reliefs caused by the synthetic energy source compared with the fossil fuel.

These reductions and burdens can be classified by comparing them in a further step with the total emissions in the respective category in Germany. In this study, the data from 2016 were used for this purpose. In the final step, the relief in terms of global warming potential is defined as -1 and the charges or relief for other environmental impacts are related to this. In chapter 5 of the detailed annex to this report, the standardisation is presented in a calculation example.

In addition to analysing individual supply paths, it is also useful to normalise and present the environmental impacts for individual product groups. For this purpose, the medians of the results in the product groups were first calculated, then compared with the environmental impacts of fossil fuels and normalised for the situation in 2016. For the hydrogen paths, sensitivity calculations (electricity supply with PV or the electricity mix 2050) were also included in the median formation.

Figure 6: **Calculated decrease or increase of burdens in 2050 compared to fossil fuels, normalised to the situation in 2016 for the medians over all paths of a product group (full-load hours of synthesis plant)**



GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

In Figure 6 the relief and burden for the median values are shown graphically. A very similar picture emerges for the Fischer-Tropsch paths and the methanol paths. Apart from the global warming potential, only the summer smog potential (POCP) shows slight relief. In all other impact categories, additional burdens arise in this assessment. For the categories water demand and cumulative energy demand (CED), these are of the same order of magnitude as the relief in the category global warming potential. For the eutrophication potential (EP) it is around half the GWP.

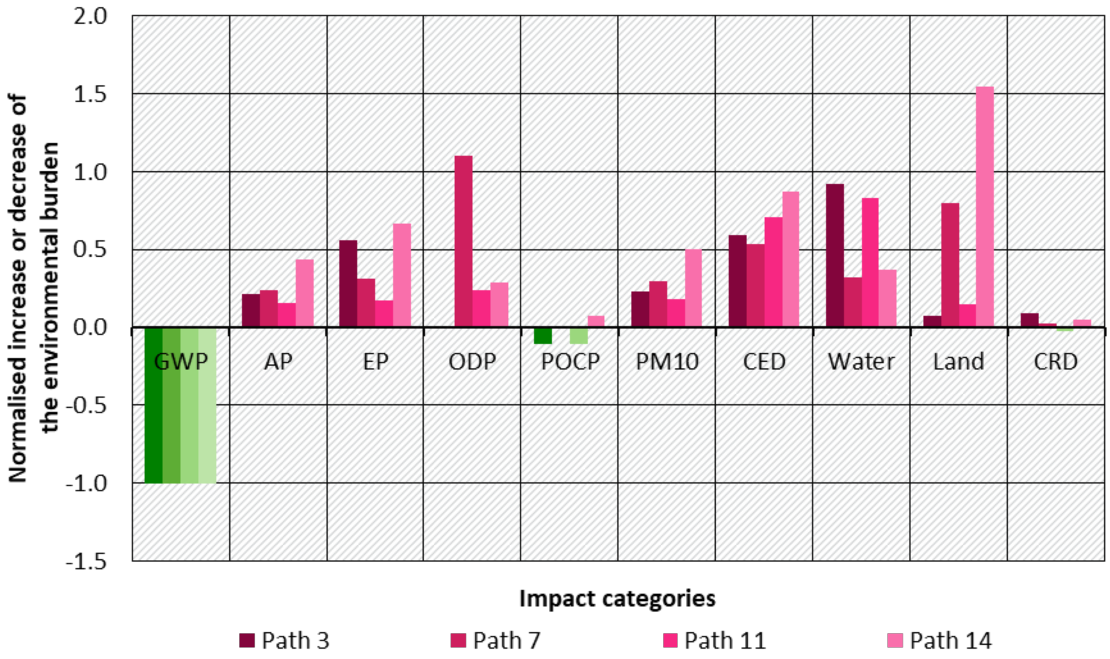
The median values for synthetic natural gas (SNG) follow a similar pattern but are better than those for Fischer-Tropsch fuels and methanol for almost all categories. Hydrogen paths perform similarly to SNG in this analysis but are significantly better in the "land" category.

However, the selection of paths shown in chapter 2.4 influences these results. For example, eight out of twelve SNG paths use either photovoltaics or concentrating solar power (CSP) as a source of electricity, both of which have a relatively large area requirement. The median of the results is accordingly high. For methanol, on the other hand, only eight out of 20 paths are calculated using PV or CSP, and for hydrogen only two of the sensitivity calculations.

The trend is the same for all product groups: on average, the production of P(B)tX energy sources could still be associated with significant environmental impacts in 2050. However, most of these impacts will come from the production of relatively few materials for power generation and synthesis plants as well as for pipelines and transport ships.

Further cross-path statements can be obtained by looking at individual path groups that differ in whether and what kind of biomass is used. This is shown exemplary in Figure 7 to Figure 9 for Fischer-Tropsch fuels.

Figure 7: Calculated decrease or increase of burdens in 2050 compared to fossil fuels, normalised to the situation in 2016 for fully electricity-based FT-paths (full-load hours synthesis plant)

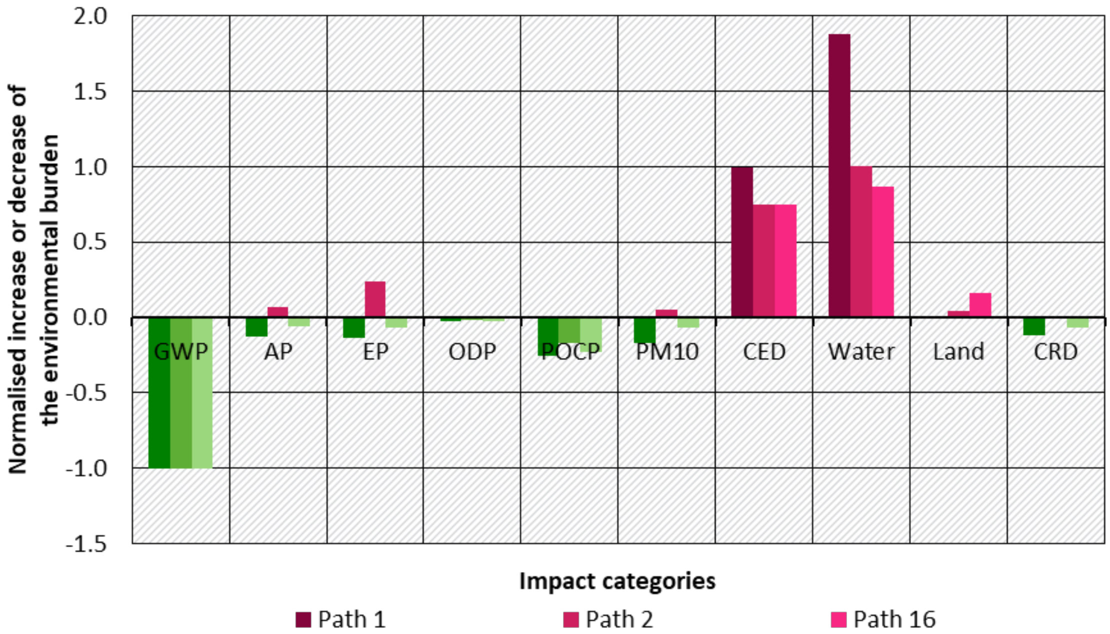


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

Figure 7 shows the normalised relief and burdens for four paths in which Fischer-Tropsch fuel is produced from electricity and CO_2 (fully electricity-based paths). For all impact categories the same pattern as for the medians of the product groups in Figure 6 is shown. The differences between the paths are mainly due to the use of different electricity sources. In path 14 the use of PV electricity leads to higher values for acidification, eutrophication, particulate matter and land use. Path 7 shows a particularly high potential for ozone depletion resulting from the production of salts for heat storage in CSP power plants.

Figure 8: Calculated decrease or increase of burdens in 2050 compared to fossil energy sources, normalised to the situation in 2016 for FT-paths with bio-residuals



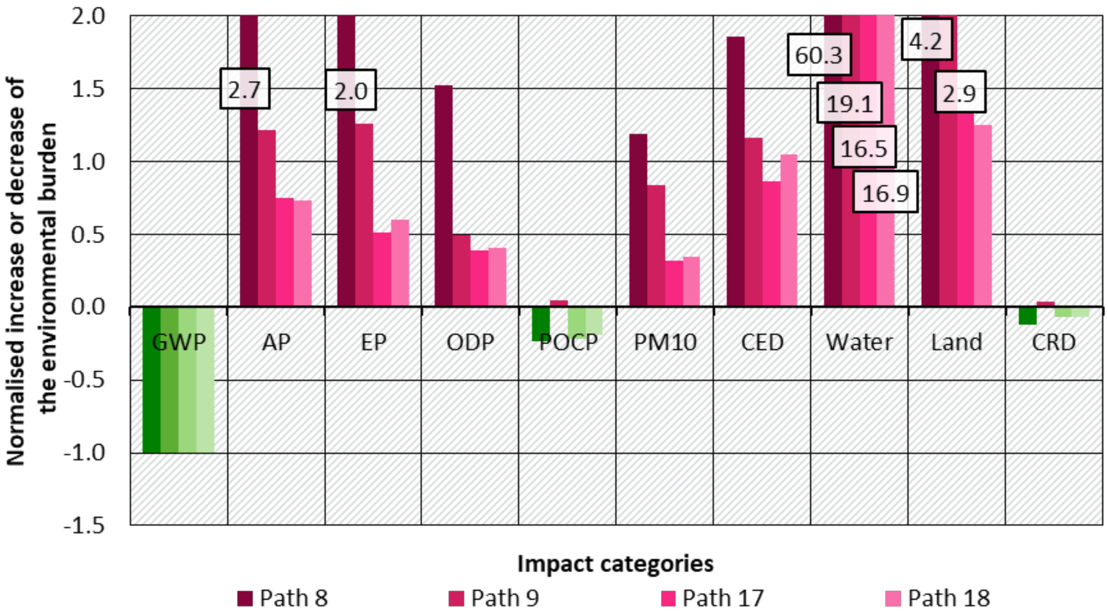
GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

Figure 8 shows the normalised relief and Burdens for three paths in which Fischer-Tropsch fuel is produced from bio-residues. Paths 2 and 16 are PBtL paths in which electrolytically produced hydrogen is also used. In contrast to pure PtL paths, significantly less electricity is required, and the residues are included in the balance in accordance with the LCA convention without environmental burdens from cultivation. This is why most environmental categories show relief compared to the production of fossil fuels. In future, this allocation and thus the ecological assessment could change (see section "Limitations of the LCA approach" in chapter 3.4)

The particularly high cumulative energy input and water demand in path 1 results from the poorer utilisation of biogenic carbon in pure BtL synthesis.

Figure 9: Calculated decrease or increase of burdens in 2050 compared to fossil energy sources, normalised to the situation in 2016 for FT-paths with cultivated biomass



GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

FFigure 9 shows the normalised relief and burden for four paths in which Fischer-Tropsch fuel is produced from poplar wood from short rotation coppice (cultivated biomass). In comparison to the fully electricity-based paths and those with bio-residuals, the values here are almost always considerably worse. In particular, the use of mineral fertilisers leads to high levels of pollution in the categories acidification, eutrophication and summer smog. Water and land requirements for cultivated biomass are also very high. The extremely high environmental burdens in path 8 also result from the poorer utilisation of biogenic carbon in pure BtL synthesis.

3.4 Conclusions

In a summary of the LCA results, this chapter identifies those factors which significantly influence the environmental impacts of the provision of synthetic energy carriers based on renewable energies. In addition, possible conflicting consequences for paths and path groups are identified – for example, if particularly low greenhouse gas emissions are accompanied by high values in other impact categories.

A central question is first of all what climate impact synthetic energy carriers have and whether they fare better compared with fossil reference products:

- Even in the reference year 2015, there are already some supply paths based on renewable electricity or biomass that achieve a reduction of almost 80% in global warming potential compared with the fossil reference. However, the majority of the paths does not achieve this reduction and some of them lie even significantly higher. Some supply options are even within the range of the fossil reference (paths 10, 32, 48 with CO_2 from the air and PV as an electricity source in Germany) or even perform worse than these (path 61 with CO_2 from a lignite-fired power plant in oxyfuel operation).
- In 2050, most paths are 80% and some also just under 90% below the fossil reference. These greenhouse gas emissions could only be avoided to a large extent if renewable energy carriers were fully used along the entire production chain. A reduction of 95% is only achieved by individual paths, namely the (P)BtL paths with straw or residual forest wood as raw material.
- Particularly unfavourable from the perspective of global warming potential is the production of synthetic energy carriers using electricity from the general power supply i.e., the current electricity mix. The global warming potential of these energy carriers is up to 350% of the fossil reference for the year 2015.
- In "stand-alone" mode with supply from only one renewable generation technology, the electrolysers, CO_2 capture plants and synthesis plants can either run only at the full load hours of the renewable power source coupled to the plant (considered in this study in the "full load hours power source" mode of operation) or storage tanks for hydrogen/CO_2/electricity must be used.
  - The operating case "full-load hours power source" leads to an increased global warming potential of the fuels, since the emissions from the construction of the plants are credited to a smaller quantity of produced energy carriers over their lifetime. In extreme cases, this doubles the global warming potential (e.g., path 32: methanol with CO_2 from the air and PV as an electricity source in Germany)
  - The environmental impacts of the construction and operation of storage facilities were not considered in this study.
- The type of renewable electricity source plays a crucial role in the global warming potential of electricity-based supply paths:

- The production of the electricity generating plants is associated with greenhouse gas emissions that are generated in the upstream chain, i.e., mainly in the production of the materials steel, concrete, copper, and aluminium. This is still the case – to a lesser extent – in 2050, even if the production processes improve significantly according to the assumptions in Chapter 2.3.1[1].
- Due to the upstream chains, electricity generation with photovoltaics still has the greatest global warming potential of renewable energy carriers in 2050, followed by concentrated solar power, geothermal energy, wind onshore, wind offshore and hydropower. This also applies to locations with favourable conditions for photovoltaics – in this study, for example, electricity generation in Morocco and Saudi Arabia – with high full-load hours. At rather unfavourable PV locations – in this study: Germany – the global warming potential per kilowatt hour of electricity generated is therefore even greater.
- Accordingly, the supply paths with high electricity demand and electricity sources with high global warming potential at rather unfavourable locations show the worst overall results. Examples of this are paths 10 (FT), 32 (methanol), 48 (SNG) with CO_2 capture from the air and photovoltaics as an electricity source in Germany.

► When transporting products from abroad, there are differences between liquid and gaseous energy carriers.

- For liquid energy carriers, transport by tanker contributes relatively little to the potential for global warming. The alternative use of high-voltage direct current transmission leads to similarly low values.
- For synthetic natural gas (SNG), the transport options differ more significantly due to methane emissions: transport by liquefied natural gas tanker has the greatest global warming potential (2050: 3 g CO_2eq/MJ), followed by pipeline transport (2050: 1 g CO_2eq/MJ). The use of high-voltage direct current transmission leads to the lowest values (2050: 0.5 g CO_2eq/MJ)

► Paths using biomass as a raw material perform better on average than electricity-based paths in terms of global warming potential.

- In particular, supply paths that use biogenic residues (straw, residual forest wood, organic waste) show the lowest values. This is mainly due to the fact that no burdens from cultivation are attributed to them.
  PBtL syntheses using the same raw materials make better use of these, but – depending on the coupled power source – show a significantly higher global warming potential. It is therefore also unfavourable to operate them with the general electricity mix, as long as it still contains a larger proportion of fossil energy carriers.

[1] It is assumed, as in the RESCUE study, that the world outside Europe is also undergoing a transformation towards greenhouse gas neutrality but delayed by 10 years.

- For cultivated biomass (wood from short-rotation plantations, silage maize), emissions during cultivation and harvest lead to a higher global warming potential – and to high environmental impacts in other impact categories.
- In 2050, biomethane paths have a higher global warming potential than synthetic natural gas. The reason for this is the methane losses in the energy supply for the operation of the plant, in particular the processing of the raw biogas.
- Outside the framework of LCA, the biomass-based supply paths are subject to a number of restrictions. In particular, the availability of these energy carriers may be restricted by limited potential and competition for use.

In contrast to the global warming potential, all supply paths in most other impact categories show a significantly higher environmental impact compared to the fossil reference. If large quantities of synthetic energy carriers are used in 2050, this may result in a considerable additional burden, which in many impact categories is of a similar order of magnitude to the relief in the GWP (Chapter 3.3)

- ► The acidification potential in 2050 for the median of all supply paths is twice as high as the fossil reference. This is mainly due to emissions from steel, copper, and aluminium production for electricity generation plants. Paths with cultivated biomass perform particularly badly, as the use of fertilisers there leads to considerable ammonia emissions. Geothermal electricity generation in Iceland is associated with very high acidification due to H_2S emissions.
- ► The eutrophication potential in 2050 for the median of all supply paths is about 3.8 times higher than the fossil reference. The reason for this is also emissions from steel, copper, and aluminium production. Paths with cultivated biomass again perform particularly badly, as the use of fertilisers leads to considerable ammonia emissions.
- ► The ozone depletion potential for the median of all supply paths for the year 2050 is also 3.2 times the fossil reference value, while the summer smog potential is around 15% lower. In terms of ozone depletion, the paths with concentrated solar power (CSP) and biomethane production stand out particularly negatively. In the case of CSP, the liquid salt heat storages are responsible, which cause significant N_2O emissions during the production of the salt. In the case of biomethane, it is the fermentation residue storage and output and the emissions from the internally used biogas CHP (electricity and heat for the operation of the plant).
- ► Cumulative energy use as a measure of the overall efficiency of the supply paths will decrease from 2.3 MJ/MJ to around 2 MJ/MJ in 2050, still 55% above the fossil reference. At the same time, this value means that only half of the electricity used is stored as energy in the end products.
- ► For the median of all supply paths in 2050, the particulate matter pollution caused by synthetic energy carriers is twice as high as the fossil reference. The paths with cultivated biomass and biomethane paths with amine scrubbing again stand out particularly negatively.

- For the median of all supply paths, the land use in 2050 is around 6,800 times greater than the fossil reference. Here, it is mainly the paths with electricity from photovoltaics and concentrating solar power, as well as paths with cultivated biomass, which require a very large amount of land.
- Water consumption for the median of all supply paths in 2050 is also around 5.7 times higher than the fossil reference. The supply paths with cultivated biomass perform particularly poorly.
- For the median of all supply paths in 2050, the cumulative raw material requirement increases by about 10% compared to the fossil reference and shifts from energy and mineral raw materials to metallic raw materials.

A cross-product assessment is only possible and useful to a limited extent, because

- the products have different applications and purposes (fuel, combustible, chemical base material, reducing agent in industry),
- the use phase is not considered in this study. Environmental impacts resulting from incineration, which differ from product to product, are not taken into account and
- a comparable number and diversification of supply paths was not used for all products.

A comparison of the products purely in terms of calorific value shows that the production of hydrogen has the lowest environmental impact, followed by synthetic natural gas, Fischer-Tropsch fuels and methanol. This ranking also reflects the increasing complexity of synthesis plants.

Limitations of the LCA approach

The validity of the studies carried out is limited in the following points and should be improved in subsequent studies:

- The use of waste heat from the synthesis plants for the separation of CO_2 is only possible if they are directly coupled. Decoupled supply paths would lead to less favourable results.
- The environmental impacts of storage facilities for CO_2, hydrogen and electricity were not included. This would make the results less favourable.
- According to current conventions, the biogenic residues were treated as "waste for recycling" and therefore do not bring any ecological burdens from cultivation. If these materials are used in large quantities in the future for synthetic energy carriers or in other material or energy uses, they may have to be treated as recyclable materials or by-products, which are proportionately assigned the burdens of cultivation. This would worsen the results for all supply paths with agricultural residues.
- Indirect environmental impacts of biomass use, such as direct and indirect land use changes, were not considered in this study.

- The data on the construction of the synthesis plants are taken from the EcoInvent life cycle assessment database and only represent a general type of plant (e.g., "Chemical Factory Organics"). Specific plant data would increase the accuracy of the results.
- For the countries considered, only full-load hours were used for average good locations. A differentiation according to ranges is conceivable.
- The use phase of the energy carriers was not considered, with the exception of the global warming potential. Here, synthetic energy carriers could have advantages over the fossil reference, e.g., due to lower pollutant contents.
- The transformation of the background system (Chapter 2.3.1) could only be modelled for electricity supply, the most important key technologies, processes, and materials. Furthermore, as in the RESCUE study, it is assumed that the world outside Europe is also undergoing a transformation towards greenhouse gas neutrality, but with a delay of ten years. For subsequent studies it would be interesting to know the environmental impacts associated with the production of synthetic energy carriers, when the global economy is completely defossilised and this transformation is fully reflected in the LCA model of the background system.

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