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Detailed analyses of the system comparison of storable energy carriers from renewable energies

Annex

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Detailed analyses of the system comparison of storable energy carriers from renewable energies

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Abstract: Detailed analyses for the 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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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 Membrane ELectrolysis)
PtG	Conversion of electricity to gaseous secondary energy carriers (Power-to-Gas)
PtL	Conversion of electricity to liquid secondary energy carriers (Power-to-Liquids)
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 Introduction

1.1 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.

1.2 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 current and estimated future technical data were documented (Chapter 2). The nature of the systems under consideration and the long reference period of the LCA analysis - 2015 to 2050 - led to methodological challenges. The processes of energy supply and conversion are still in the early stages of development in some cases. 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 (Appendix A) 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 sources for the supply paths (Chapter 4).

In the next step, the modules were combined into technically reasonable paths. Simplified screening LCAs then allowed to identify disadvantageous and favourable supply paths in particular. The modular design showed the influence of different production steps and technology options and their possible combinations on the overall results. From the large number of technically feasible combinations, those supply paths were then selected that covered as broad a field as possible. Especially those paths were included from which particularly large or small environmental impacts could be expected (Chapter 5.2).

The selected paths were finally analysed using the life cycle assessment method (Chapter 5.3) and the costs of supply were estimated (Chapter 6).

2 Technology data for the provision of synthetic energy carriers

This chapter constitutes the basis for characterising and evaluating possible supply paths for the provision of hydrogen, synthetic methane and synthetic liquid hydrocarbons (e.g., methanol, paraffin, petrol and diesel). The focus here is on process routes based on biomass and/or electricity from renewable energies. For the flexible definition of the supply paths, individual process steps - from electricity/biomass generation and energy carrier production in Germany and abroad and their transport to Germany - were defined as modules. Only technically advanced or already available processes were considered. The selected technology modules each represent at least one 'state of the art' technological process variant. As this report is a translation of the German version that was published in early 2020, most technology data refer to the years 2017/18. The technology provided the data basis for all subsequent LCAs and the economic technology comparisons.

In this chapter technology profiles are presented in which the technical parameters of the respective module are documented for further use in the following analyses steps. On the one hand, these are descriptions of reference plants for the respective module. On the other hand, data sheets corresponding to the modules have been prepared which document current technical data. These data are available on the website of the Federal Environment Agency. As data sources, both detailed technological knowledge from own research projects and existing literature was used. For better clarity, the sources are documented within the respective technology profiles.

First, the modules for the synthesis of hydrogen and gaseous and liquid hydrocarbons, which were investigated in the project, are described. This is followed by the modules for carbon sources, water treatment and the transport options of the energy carriers.

2.1 Modules for the production of synthetic energy carriers

2.1.1 Electrolysis and hydrogen supply

In electrolysis, water molecules are decomposed into hydrogen and oxygen by direct current. Two partial reactions take place at the two electrodes (cathode and anode). Hydrogen is produced at the cathode and oxygen at the anode. The necessary charge balance between the two partial reactions is achieved by ion conduction via an electrolyte. A separator (gas separating membrane) is placed between the reaction spaces of the electrodes, which ensures the separation of the product gases hydrogen and oxygen. Several electrolysis cells can be connected in series or parallel to one component, the stack.

Water electrolysers can be divided into three relevant types according to the type of electrolytes used:

- The alkaline electrolysis (AEL) with aqueous potassium hydroxide or sodium hydroxide as electrolyte,
- the polymer electrolyte membrane electrolysis (PEMEL) with a proton-conducting membrane as electrolyte and
- the Solid Oxid Electrolysis Cell (SOEC) with a ceramic ion conducting membrane.

Theses electrolysis technologies have different levels of technological readiness. Since DLR is conducting its own research in the field of all three electrolysis types, the literature sources could be evaluated and ordered on the basis of these experiences.

Module 1: Alkaline electrolysis (AEL)

Technology description

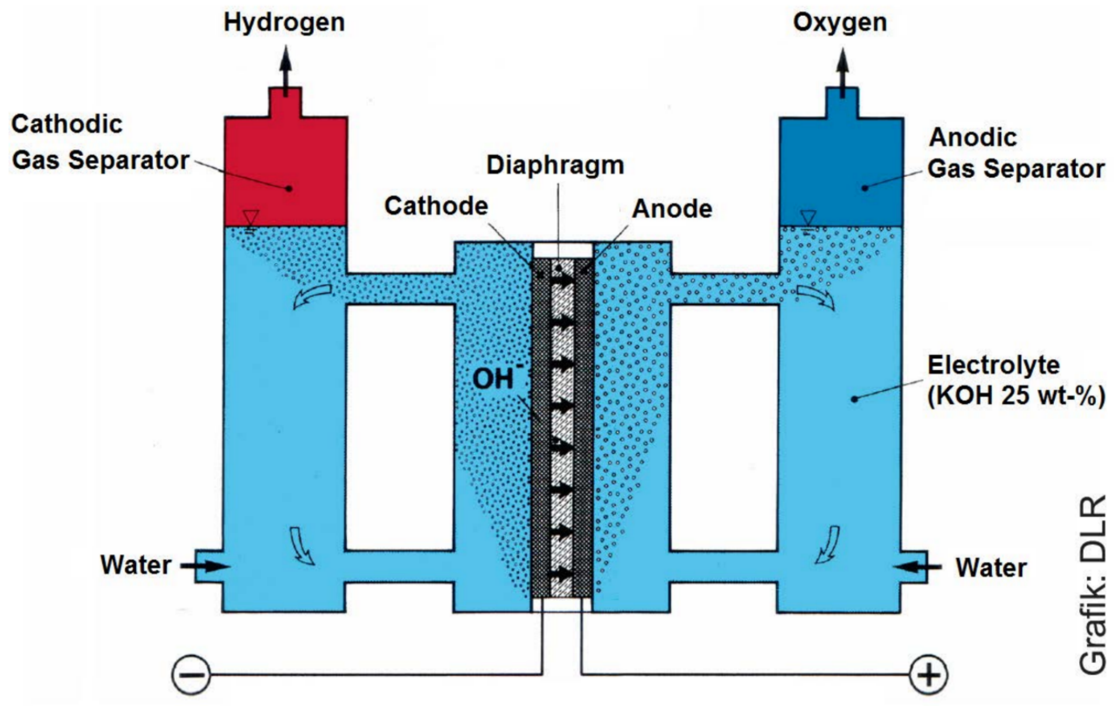
The alkaline electrolysis is based on the electrical splitting of water at high pH values. The reaction takes place in the electrolyser as follows:

Anode $2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$

Cathode $2\ OH^- \rightarrow H_2O + ½\ O_2 + 2e^-$

The functional principle of an alkaline electrolysis cell is shown in Figure 1.

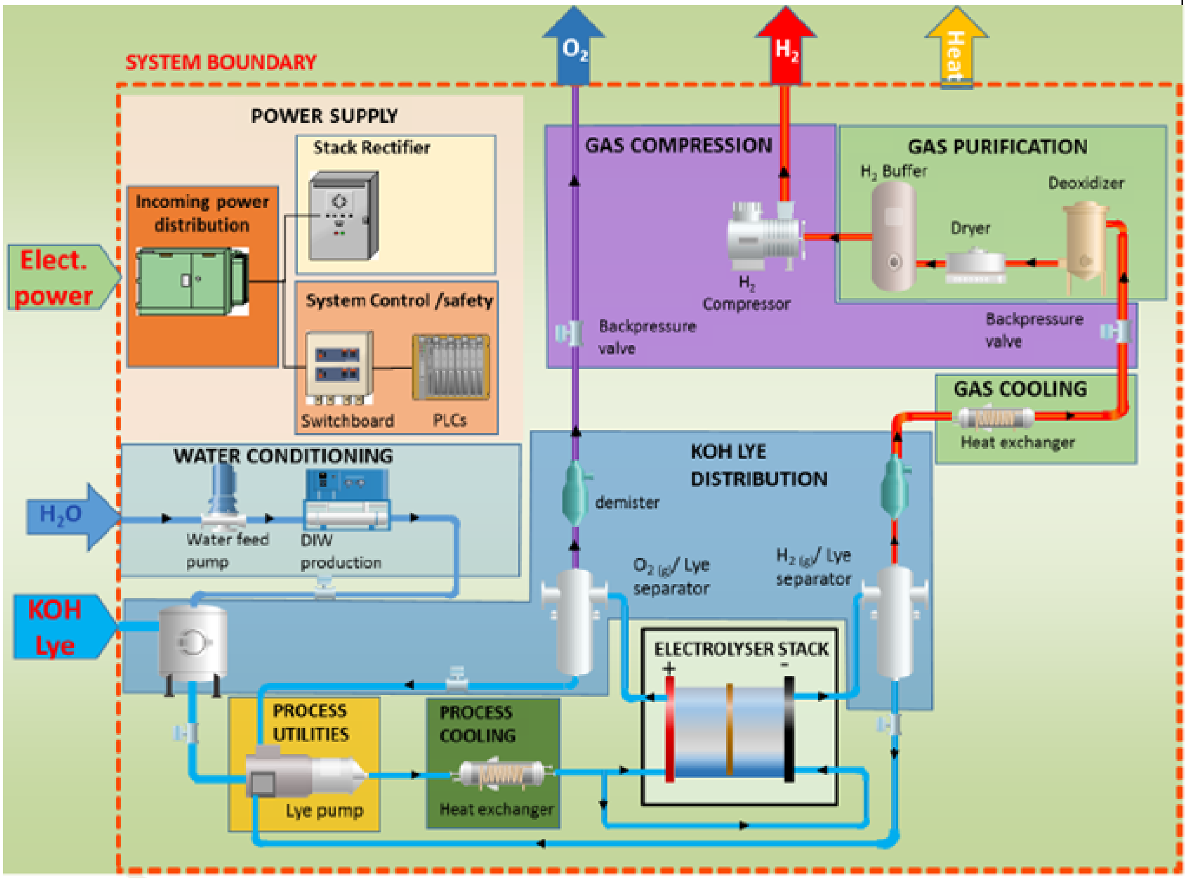
Figure 1: Operating principle of an alkaline electrolysis cell



Source: DLR

In addition to the cell stack, the alkaline electrolyser contains a transformer and rectifier, a water treatment plant, gas analysis, gas scrubber, gas cleaner, gas storage and compressors. In pressurised electrolysers, the system pressure is set via pressure control valves. The lye is circulated by a circulation pump, in some models also pumpless via convection. The operating temperature is controlled by a heat exchanger. After the product gases mixed with lye leave the alkaline electrolysis cell, the gas and lye are separated in water separators and the lye is returned to the circuit. The finer lye and water particles in the product gases are separated by a demister. Further components required are a control and monitoring unit and a system for providing deionised feed water (feed water pump and ion exchanger). Figure 2 shows the construction of an alkaline electrolyser.

Figure 2: Common setup of an alkaline electrolyser including subsequent gas treatment



Source: JRC 2018

The following alkaline electrolysers are currently available on the market. In most cases these are commercial products, some of which have been available for many years in a similar form, with only minor modifications.

Some electrolyser systems are delivered in containers. This allows flexible and mobile use and saves costs by assembly and testing at the supplier's site. Larger electrolyser units, however, are not designed to be mobile. There are hardly any restrictions for the installation site.

Environmentally critical is the possible release of highly concentrated potassium hydroxide lye, which is, however, safeguarded by design. The alkaline electrolyser does not contain any other environmentally and resource critical materials. The electrodes are made of nickel, containers and pipes of stainless steel, plastic frames in a stack e.g., of PEEK (polyetheretherketone), seals of Teflon, the diaphragm separating the gas chambers of PEEK and titanium dioxide. The oxygen produced is usually not used but released into the environment. The reasons for this are the high costs of storage, the safety regulations for oxygen storage and the low demand. Waste is generated from KOH lye in small quantities as well as KOH-contaminated wear parts of the plant, which are replaced during maintenance.

Manufacturer	Product	Electric power (kW)	Special energy (kWh/Nm^3 H_2)
Hydrogenics	HySTAT 60 (Hydrogenics 1, 2013)	515	5.2
NEL	NEL A (NEL, 2014)	2134	4.4

Water electrolysis Hydrotechnik GmbH	EV 150/60 (HT 2, 2014)	1188	5.28
ELT Electrolysis Technology	BAMAG (ELT 1, 2014) (gas dry, 0 °C)	2208	4.3-4.6
ELT Electrolysis Technology	LURGI (ELT 2, 2014) (gas dry, 0°C)	6510	4.3-4.65
Teledyne Energy Systems	(Teledyne, 2018)	n.a.	n.a.

Technical development trends and development goals

The cell design determines the resistance of the cell and thereby the current density in operation. Today's alkaline electrolysers operate at 0.5 A/cm^2, which is to be increased to a value of 1 A/cm^2 by 2030 (PlanDelyKaD 2014). However, this can only be achieved if the internal electrical resistances are further reduced. This can be achieved by the so-called "zero gap" cell design. In this design, perforated electrodes are pressed against the separator, which lowers the resistance between the electrodes, since fewer gas bubbles are created between the electrodes. The perforation of the electrodes or the size of the holes must support the formation of gas bubbles and the rapid release of gas bubbles. The hole sizes must be aligned with the gas bubbles (HyFC 2010).

An increased power density can also be achieved by a smaller electrode gap with thinner, more gas-tight OH-ion conductive membranes. These membranes are commercially available, but their lifetime has to be significantly increased by further development.

Further current developments are moving towards cost reduction through standardised and automated production as well as modularisation and thus larger quantities. In addition, work is being done on increasing the performance dynamics of electrolysers in order to respond to changing applications (previously constant hydrogen production for the chemical industry, future use of fluctuating regeneratively generated electricity).

A development of alkaline electrolysis towards alkaline pressure electrolysis is also currently being investigated. The advantage would be the saving of one compression stage for the hydrogen produced and thus of system costs in applications requiring pressurised hydrogen. However, disadvantages are (Shell 2017):

- The increase of the reversible cell voltage due to the high pressure
- The use of water supply pumps and circulation pumps
- The dissipation of waste heat due to the increased cell voltage
- The cost of using pressure-resistant components

Alkaline electrolysers under high pressure are therefore not expected to be widely used in the next few years.

Current importance and outlook for 2030/2050

Alkaline electrolysers are currently the only established, reliable and available technology in megawatt size. Due to the further developments described above, they should continue to be competitive with the other electrolysis types.

Their dynamic operation is limited. Today, operation is usually only possible in the range of 40 - 70% of the rated power. In this range, the electrolyser can follow the changes in available power, provided these do not have too high gradients. Frequent and fast switching on and off of the electrolyser is not possible or reasonable. Therefore, an alkaline electrolyser, which is operated in a stand-alone system with direct coupling to a regenerative energy source, cannot fully utilise the energy provided. Further developments towards higher dynamics of alkaline electrolysers are in the research stage.

Hydrogen from centralised and decentralised electrolysis plants (electrolysis technologies are not differentiated here) can be made available in future for just under 6 €/kg (for the centralised plant) and slightly less than 8 €/kg (for decentralised electrolysis) (Plan-DelyKaD 2014). Here the electricity price is a key influencing factor alongside capacity utilisation and the number of full-load hours worked.

Technological parameters

Technology data: (Smolinka et al., 2011)

This data are assumed for a complete electrolysis system in which the submodules plant and operation are integrated. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050***
Stack efficiency	(based on lower calorific value)%	71	73	80
System efficiency	(based on lower calorific value)%	67	69	72
Operating temperature	(°C)	80	85	95
Maximum operating pressure	(bar)	30	60	60
Current density	(A/cm^2)	0.4	0.6	0.8
Minimum partial load capacity	%	40	20	20
Available stack size	(m^3/h)	450	1250	1750
Lifetime	(h in operation)	75,000	90,000	90,000
Service life system incl. overhaul	years	30	30	30

*estimated values

Explanation of the parameters: Efficiencies determine the efficiency in operation. A high operating temperature of the stacks increases the efficiency, but due to a higher material stress often leads to shorter lifetimes or more expensive materials and longer starting times until the optimum operating point is reached. Pressure from the electrolyser makes it possible to dispense with an additional compressor in some applications, but leads to higher system costs than unpressurised operation. A high current density means more hydrogen is produced from the unit, thus a lower footprint and lower investment costs. Partial load capability affects the ability to couple the electrolyser to fluctuating power sources.

Components

- Stack
- Transformer
- Rectifier
- Water treatment plant
- Gas scrubber
- Gas purifier
- Gas storage
- Compressors

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Module 2: PEM electrolysis

Technology description

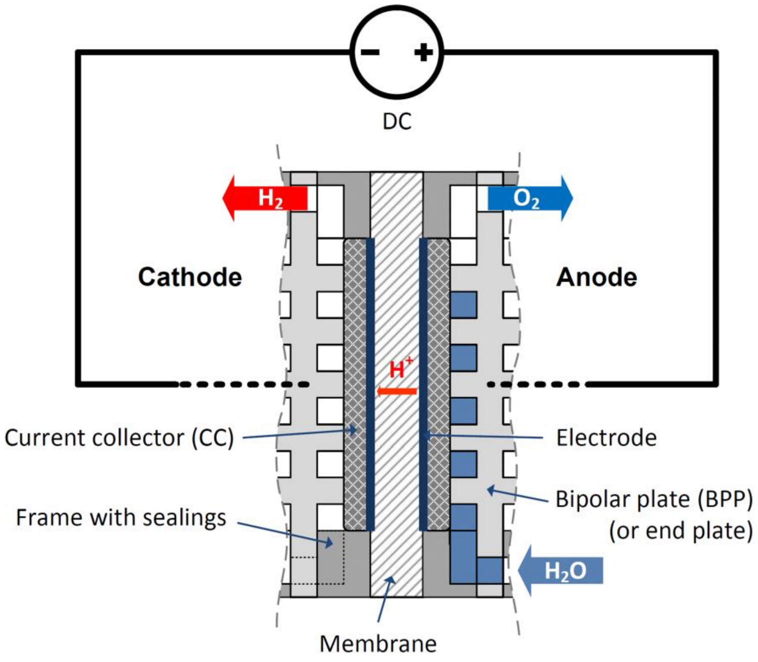
The PEM electrolyser (proton exchange membrane) is based on the electrical splitting of water at neutral pH value. The reaction in the PEM electrolysis takes place as follows:

Anode $2 H_2O \rightarrow 4H^+ + O_2 + 4e^-$

Cathode $4 H^+ + 4e^- \rightarrow 2H_2$

The functional principle of a PEM electrolysis cell is shown in Figure 3 (Plan-DelyKaD 2014).

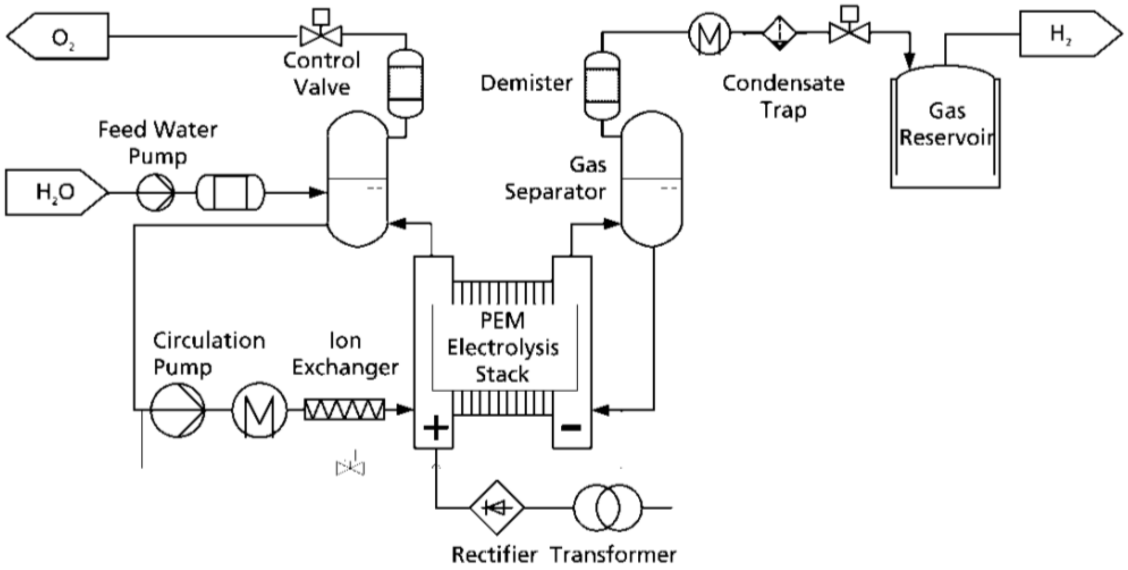
Figure 3: Operating principle of a PEM electrolysis cell



Source: DLR

The PEM electrolyser contains the cell stack, transformer and rectifier, gas analysis, gas cleaner and gas storage. The system pressure is set via pressure control valves. Figure 4 shows the set-up of a PEM electrolyser module.

Figure 4: Common construction of a PEM electrolyser without further gas treatment



Source: Plan-DelyKaD 2014

The feed water is circulated by a circulation pump. The operating temperature is controlled by a heat exchanger. After the product gases leave the PEM electrolysis cell, the entrained water is separated in a water separator and returned to the circuit. The finer water particles in the product gases are separated by a demister. The system pressure is set via pressure control valves. Further components required are a control and monitoring unit and a system for providing deionised feed water (feed water pump and ion exchanger not shown) (Plan-DelyKaD 2014). Currently the following PEM electrolysers are available on the market (Plan-Delykad 2014). The overview clearly shows that the development status of PEM electrolysis is very broad.

Manufacturer	Series (operating pressure)	H_2 rate (Nm³/h)	Status (number of systems sold)
CETH (FR)	E series (14 bar)	5 - 60	Prototypes in field test
Giner (US)	OGP (207 bar) LPE (55 bar) N.N. (85 bar)	13 ~ 15 56	Defence sector Defence sector Under development (petrol stations)
h-tec (DE)	EL 30 (30 bar)	0.4 – 2.4	Prototype
Areva (FR)	N.N. (30bar)	1 - 10	Single pieces for nuclear power plants
Hydrogenics (CA)	Hylyzer 65 HySTAT-P (30 bar)	- 30.0 250.0	Development rests Prototype development
ITM Power (GB)	HLab/HPac/HBox (15 bar) HFuel (?) HGas (80 bar)	0.036 – 7 60 60	Pre-series, field test Prototype in field test Prototype in field test
Proton Energy Systems (US)	Hogen GC, S (13.8 bar) Hogen H (15/30 bar) Hogen C (30 bar) HP (165 bar)	0.02 – 1.05 2.0 – 6.0 10 – 30	Commercial (~ 1100) Commercial (~ 150) Prototype, pre-series in 2010 Defence sector

Siemens (DE)	Silyzer 100 (50 bar) Silyzer 200 (35 bar) (*)	20 (*) 250 (*)	Prototype for field test Prototype development
Sylatech (DE)	N.N. (30 bar)	- 0.12	Individual production

(*) Data estimated

These PEM electrolyser systems are delivered in containers. This allows a flexible and mobile use. Please note that most systems do not have a cooling and heating system to save costs. The systems are usually cooled with water, whereby the amount of heat generated depends on the operating current density (Lettenmeier 2016).

As materials critical to the environment and resources, the electrode materials are particularly relevant in PEM electrolysis, e.g., Platinum and Iridium. The oxygen produced is usually discharged directly into the environment and not used as raw material. The reasons for this are the high costs of storage, the safety regulations that oxygen storage entails and the low demand.

In addition to oxygen, resin waste is also produced from the ion exchanger of the water treatment plant. These can however be regenerated.

Technical development trends and development goals

PEM technology has been used in niche applications for decades - for small applications and at high costs. PEM electrolysers have been significantly improved in recent years, with large scale systems still in the development and prototype phase. PEM electrolysers in the megawatt range are only just on the threshold of commercialisation. Therefore, a long-term forecast of the development of this technology is associated with great uncertainty.

The dynamic properties of PEM electrolysers are better than those of alkaline electrolysers. An operation is usually possible between 10-150% (or more) of the nominal power. In this range the system can follow dynamic changes of the available power. A short switch-off of the electrolyser with a quick subsequent start is possible with some models. This allows a PEM electrolyser to be operated in a stand-alone system with direct coupling to a regenerative energy source and to use a large part of the available energy.

Research and development activities in the field of PEM electrolysis are mainly focused on cost reduction. This is attempted, among other things, by using more cost-effective catalysts in the electrolyser stack. Further cost reductions are expected in the area of flow distributors (through which the water is pumped along the electrodes), bipolar plates (the electrical connection of each cell in the compound) and membranes, which together account for up to 50% of the stack costs (Mergel 2013). These developments are expected to reduce investment costs, which currently amount to more than 2000 € per kW installed capacity, to less than 600 € per kW installed capacity (Mergel 2013).

Current importance and outlook for 2030/2050

Long-term goals in the development of PEM electrolysis are the expansion to the double-digit megawatt class, as well as new (low-cost) materials and the necessary production technologies.

Another issue is overload - operating an electrolysis system above the nominal operating point for a limited period of time (Plan-DelyKaD 2014). In future, a system should have an overload tolerance of at least 30 minutes at a load of 150% for a 5 MW system and 200% for a 100 MW system (Plan-DelyKaD 2014).

Technological parameters

Technology data: (Mergel 2013), (Mergel 2013a), (Smolinka 2011) and (Carmo 2013). This data are assumed for a complete electrolysis system, in which the submodules plant and operation are integrated. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050 *
Stacking efficiency (in relation to the lower heating value)	(based on calorific value)%	71	75	85
System efficiency (in relation to calorific value)	(based on calorific value)%	67	71	80
Operating temperature	(°C)	80	90	90
Maximum operating pressure	(bar)	85	100*	100*
Current density	(A/cm^2)	2.0	2.5	3.5
Minimum partial load capacity	%	10	5	5
Available stack/system size	(m^3/h)	250	500*	750*
Lifetime	(h in operation)	50,000	80,000	80,000
Service life system incl. overhaul	years	20	30	30
Precious metal requirements**	(mg/cm^2)	2(Ir);0.5-1(Pt)		

(*) Data estimated
(**) The demand for precious metals should decrease over time, but by how much cannot be estimated. If the LCA shows a major impact, a sensitivity analysis would be carried out.
Explanation of the parameters: Efficiencies determine the efficiency in operation. A high operating temperature of the stacks increases the efficiency, but due to a higher material stress often leads to shorter lifetimes or more expensive materials and longer starting times until the optimum operating point is reached. Pressure from the electrolyser makes it possible to dispense with an additional compressor in some applications, but leads to higher system costs than unpressurised operation. A high current density means greater hydrogen production from the unit, thus a smaller ecological footprint and lower investment costs. Partial load capability affects the ability to couple the electrolyser to fluctuating power sources. Precious metal demand causes costs and is important for resource and LCA analysis. The remaining parameters are self-explanatory.

Components

- Stack
- Transformer
- Rectifier
- Water treatment plant
- Gas analysis
- Gas purifier
- Gas storage

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Module 3: High Temperature Electrolysis (SOEC)

Technology description

High temperature electrolysis (SOEC, Solid Oxid Electrolysis Cell) is based on the electrical decomposition of water at high temperatures between 500 and 850 °C (E4Tech 2014). Water vapour is converted at the cathode into hydrogen and oxygen ions, which are negatively charged and can therefore migrate through the ceramic electrolyte (usually made of yttrium oxide or zirconium oxide) to the anode. There they react to form oxygen by releasing electrons. The reaction proceeds as follows:

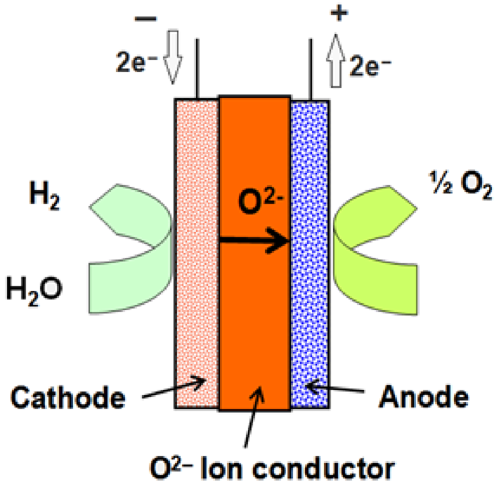
Anode $2\,O^{2-} \rightarrow O_2 + 4\,e^-$

Cathode $2\,H_2O + 4e^- \rightarrow 2\,H_2 + 2O^{2-}$

For the chemical dissociation of water vapour, less electrical current is required compared to liquid water. The energy to vaporise the water can be supplied both electrically and thermally. By coupling in external high-temperature heat, it is possible to provide a large part of the required energy, e.g., in the form of process heat and to reduce the use of electrical energy. The functional principle of a high temperature electrolysis cell is shown in the following figure.

In addition to the cell stack, the high-temperature electrolyser requires a transformer and rectifier, water treatment plant, steam generator, gas analysis, gas cleaner, heating device or heat coupling and gas storage.

Figure 5: Functional principle of a high temperature electrolysis cell



Source: DLR

High-temperature electrolysis is still in the research and prototype development stage. However, the interest in this technology has increased and led to EU projects such as RelHy and Hi2H2. The high efficiency and the possibility of co-electrolysis of water and CO_2 to produce synthesis gas is particularly attractive. Internationally, research is carried out at the Institute of Nuclear Energy Technology (INET) of Tsinghua University (CN), the Korea Institute of Energy Research (KIER,KR), Kyushu University (JP) and the American DOE Nuclear Hydrogen Initiative (US) (HyFC 2010). The operation of the high-temperature electrolyser under pressure - in order to be able to release hydrogen under pressure - is possible in principle but is complex and expensive in terms of plant engineering. Therefore, SOEC plants are normally operated without pressure.

Environmentally and resource-critical materials are hardly present in high-temperature electrolysis. Essential materials in the stack are nickel and zirconium oxide, partly also high-alloy ferritic stainless steels with a high chromium content. For better conductivity, the zirconium oxide is doped with yttrium oxide. This is more expensive to extract than the other materials but is required in smaller quantities.

The oxygen produced in the electrolysis is usually discharged directly into the environment and not used as raw material. The reasons for this are the high costs of storage, the safety regulations that oxygen storage entails and the low demand.

Technical development trends and development goals

Large laboratory systems with a hydrogen production rate of 5.7 Nm³/h at an output of 18 kW are known. Current densities of more than 2.0 A/cm² were achieved in the Hi2H$_2$ project at temperatures of 680 - 1000 °C. So far only limited information is available on the lifetime of high temperature electrolysis. The degradation rate at 40,000 hours should be well below 10 µV/h in order to be able to compete with the other systems and to keep the costs of the system low. The long-term tests carried out in the Hi2H$_2$ project were described for single cells up to max. 2,500 h and short stacks (five cells) up to max. 3,500 h. For single cells the degradation rate was about 2% per 1,000 h and for the five cell system between 15% per 1,000 h (in the first 2,000 h) and 6% per 1,000 h during the next 1,500 h (0.3 A/cm² and 800 °C). In (Schmidt 2017), based on expert estimates, a lifetime of around 10,000 h is already given for today.

At higher current densities, the service life decreases significantly (Smolinka 2011). The reduction in the service life of the system is mainly due to the electrodes. In the long term, the focus is on the development of prototypes and commercial system concepts and later cost reduction.

Current importance and outlook for 2030/2050

No commercial plants exist at present. It is therefore not yet possible to give an outlook for 2030 and 2050. However, according to current knowledge, this technology is less suitable for coupling with intermittent energy carriers. The reason for this is the limited dynamics of this technology.

The potentially high efficiency of the SOEC in combination with external heat sources at high temperature levels is one of the advantages of the technology. Another advantage is the possibility of reversible operation, i.e., the same unit can produce hydrogen or generate electricity from hydrogen in fuel cell case. In this way, the hydrogen produced could be used efficiently as an energy storage medium. The third advantage of the SOEC is the possibility of co-electrolysis: in addition to water vapour, CO_2 is added, and synthesis gas (H_2 + CO) is produced. This can be used e.g., as a basic material to produce synthetic hydrocarbons. All applications are still in the development stage.

Technological parameters

The technology data for 2015 are based on (Smolinka 2011) and (Schmidt 2017). Due to the early stage of development of the technology, an update of the data is associated with very large uncertainties. For this reason, the current data for 2030 and 2050 have been used in addition to the lifetime. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Electrical stack efficiency	(in terms of calorific value)	>100%*	>100%*	>100%*
System efficiency	(in terms of calorific value)	n/a	n/a	n/a
Operating temperature	(°C)	700-1,000	700-1,000	700-1,000
Maximum operating pressure	(bar)	1	1	1
Current density	(A/cm²)	0.4-2	0.4-2	0.4-2
Minimum partial load capacity	%	n/a	n/a	n/a
Stack size on a laboratory scale	(m³/h)	5.7	5.7	5.7
Lifetime	(h in operation)	10,000	70,000	90,000
Service life system incl. overhaul	h	n/a	n/a	n/a

(*) Since part of the energy is supplied as heat, which is usually waste from another process, the electrical efficiency (i.e., the ratio of electricity consumption to the calorific value of the hydrogen produced) is above 100%.
Explanation of the parameters: Efficiencies determine the efficiency in operation. A high operating temperature of the stacks increases the efficiency, but due to a higher material stress often leads to shorter lifetimes or more expensive materials and longer starting times until the optimum operating point is reached. Pressure from the electrolyser makes it possible to dispense with an additional compressor in some applications but leads to higher system costs than unpressurised operation. A high current density means more hydrogen is produced from the unit, thus a lower footprint and lower investment costs. Partial load capability affects the ability to couple the electrolyser to fluctuating power sources.

Components

- Stack
- Transformer
- Rectifier
- Water treatment plant
- Steam generator
- Gas analysis
- Gas purifier
- Gas storage
- Heating device or heat coupling

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Module 4: Hydrogen liquefaction

Technology description

Due to its relatively low volumetric density, hydrogen cannot be stored under standard conditions for transport and use in both stationary and mobile applications. It is therefore compressed or liquefied. The choice of liquefaction technology is decisive for the energy demand.

Liquid hydrogen has been used in the space industry since the 1950s. Several dozen condensers are in commercial use worldwide. To liquefy hydrogen, it must be cooled to -253 °C. In a multi-stage, energy-intensive process, the purified gas is cooled to this temperature (Brinner 2017).

Liquid hydrogen can be produced using the Claude process with single or two-stage refrigerant pre-cooling and subsequent expansion. The Claude process uses a combination of expansion machine and Joule-Thomson expansion. A high-pressure mass flow supplied by a compressor is divided behind the heat exchanger. One part passes through the following heat exchanger and expansion valves, another part is expanded in the expansion machine and cooled down. The cooled low-pressure gas is passed through the heat exchangers in counterflow, thereby cooling the incoming high-pressure gas (spectrum 2018).

Technical development trends and development goals

The efficiencies of large hydrogen liquefaction plants are 20-30%. Conceptual plants, such as those of NTNU and SINTEF have been able to achieve efficiencies of up to 50% (Dobrota 2013).

Possible R&D approaches to increase the efficiency of condensation processes include the choice of refrigerant (neon or neon-helium mixtures instead of hydrogen or helium). Work is also being done on new processes that do not rely on the Joule-Thomson effect (Peltier elements or magnetocaloric processes). In addition, further savings can be achieved through intelligent systems technology, such as Hydrogen production at high inlet pressure or the coupling of high-pressure intermediate storage tanks with condensers. (Brinner 2017)

Current importance and outlook for 2030/2050

Since the use of liquid hydrogen is almost exclusively in the automotive sector, the efficiency of the conceptual plants of NTNU and SINTEF of 50% is to be seen here as an outlook for large-scale plants in 2030 and 2050.

Special challenges arise from a system integration of condensers in a hydrogen production process using fluctuating energy carriers (especially wind). These are due to the fact that condensers are very adynamic and are best kept constant and operated at high full load hours. Such an application therefore requires intermediate storage (Brinner 2017).

Technological parameters

The technology data for 2015 are estimated according to (Yang 2007). Ball (2009) assume an increase in capacity and the associated greater efficiency. The values of 2030 and 2050 are based on plant sizes of 70 and 215 tonnes H_2 per day

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Condensation work	kWh/kg H_2	11	10	7
Condensation work	% of LHV	33	31	22
H_2 loss due to cooling requirement in the tank	% / day	0.3	0.3	0.3
Lifetime	a	30	30	30
Full load hours	h	8000	8000	8000

Components

- Compressor
- Counterflow heat exchanger
- Expansion machine
- Relief valve

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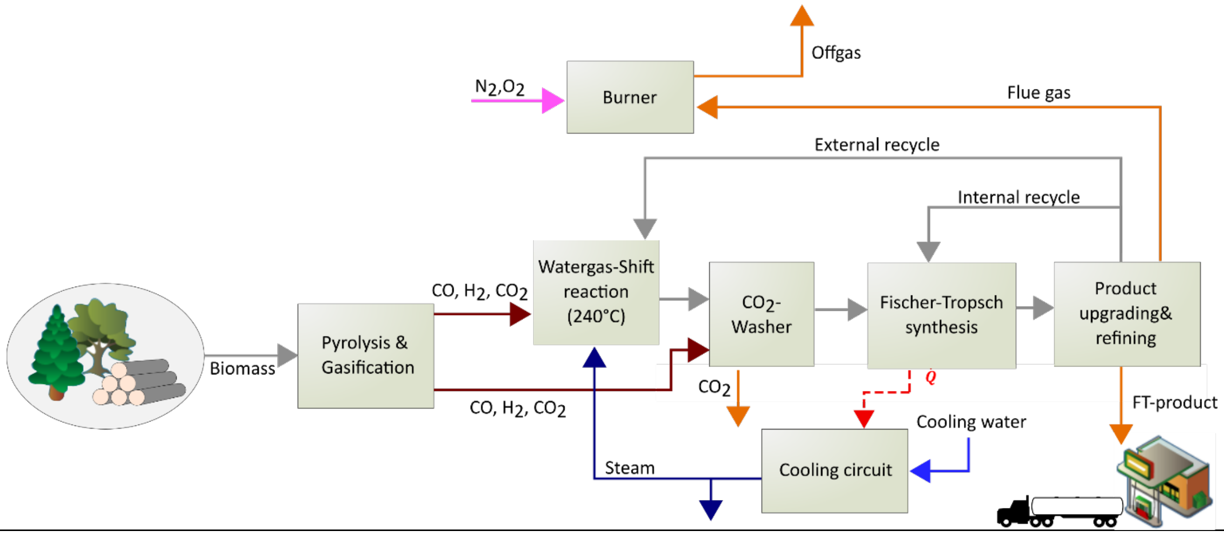
2.1.2 Production of liquid hydrocarbons

The modules for the supply of synthetic liquid energy carriers comprise the two technologies Fischer-Tropsch synthesis and methanol synthesis. The technology data are largely based on projects carried out at DLR. On the basis of extensive literature research, the respective processes were modelled with the process simulation software AspenPlus® and also economically optimised by coupling with the techno-economic evaluation tool TEPET. The results allow a consistent and 'close-to-real-life' comparison of the individual process chains, as the procedure used is based on standardised methods used in the chemical industry. When comparing the efficiencies, it should be noted that in the case of the electricity-based processes (PtL and PBtL) the energy losses of hydrogen production are not taken into account in the respective FT, MeOH or SNG process module.

Module 5: Fischer-Tropsch synthesis based on biomass (Biomass-to-Liquid, FT-BtL)

Technology description

Figure 6: Overview of the FT-BtL process chain



Source: own figure, DLR

In the BtL process, biomass is first dried and, depending on the subsequent gasifier type, pretreated/pyrolyzed and gasified in a **gasification unit.** The resulting gas is then prepared for the **Fischer-Tropsch synthesis** through **gas purification** and **gas conditioning steps.** Depending on the desired product, the synthesis is followed by separation and **refinement steps** (Albrecht 2016).

There are three common gasifier types: Fixed bed, fluidised bed and entrained flow gasifiers. For high throughput rates a fluidised bed or entrained flow gasifier is useful. In addition, the entrained flow gasifier has the advantage of a low faulty production of tar and methane due to the very short residence times at operating temperatures of 1000 - 1200 °C. Furthermore, this technology is easy to scale and is state of the art at least for coal. On the other hand, an entrained-flow gasifier requires a complex pre-treatment (pyrolysis) of the biomass, as it has to be fed into the gasifier as a pumpable mixture. For smaller plants it may therefore be advantageous to use a fluidised bed reactor (Heidenreich 2015, Molino 2016, Pereira 2012).

The gas produced in the gasifier is then cooled with water and cleaned of particles, before it is freed of further impurities (especially HCl, H_2S) by means of centrifugal separators and additional filters or sorption reactors. The synthesis gas thus obtained consists largely of CO, H_2, CO_2 and steam. In order to achieve the H_2/CO ratio of 2 required for the Fischer-Tropsch synthesis, a partial stream is fed into a water-gas shift reactor. In this reactor, water and CO are formed out of H_2 and CO_2 about 220 to 260 °C. The CO_2 is then separated in a downstream Selexol scrubber and the synthesis gas is passed to the Fischer-Tropsch synthesis.

The further process steps are established technologies. In the Fischer-Tropsch synthesis, hydrocarbons are catalytically synthesised at pressures between 20-40 bar and temperatures around 200-300 °C. Two catalysts used on a large scale dominate here: cobalt and iron. When operating with cobalt, the operating temperature can be selected lower than when operating with iron. In addition, a higher alkane/alkene ratio is achieved (Klerk 2011). The process is highly exothermic, which is why full conversion in Fischer-Tropsch synthesis is hardly achievable, as the heat cannot be removed from the system quickly enough and the resulting water deactivates the catalyst. The waxes produced in the Fischer-Tropsch synthesis are cracked in the subsequent hydrocracker at about 30-80 bar and 300-400 °C with the help of additional hydrogen and split into shorter hydrocarbons. The subsequent steps of product separation and refinement must be adjusted according to the desired end product. Unconverted synthesis gas is returned to the FT-synthesis or burned in an Oxyfuel burner to generate electricity in a steam cycle.

For the life cycle assessment of the technologies used in the process, it is necessary to consider the materials used for the plant (steel and aluminium) as well as the catalysts and washing liquids used during operation. The quantities required vary depending on the process management and must therefore be assessed individually for each process.

Technical development trends and development goals

The research focus for biomass-to-liquid technology is on the further development of biomass gasifiers and gas cleaning as well as the demonstration of the overall process (Hamelinck 2004, Swanson 2010, Tijmensen 2002).

The gasification of biomass represents a very energy-intensive process step. The correct process control depends strongly on the composition of the chosen biomass. A universally optimal solution will therefore not be found in the foreseeable future; instead, the processes must be selected and optimised for the respective conditions (Tijmensen 2002).

Gas purification is very costly, especially due to the different compositions of the individual biomasses, as high fluctuations in the composition of the pyrolysis gas must be expected.

The Red Rock Biofuels project with a planned capacity of 1,040 bbl/d uses wood as a raw material. Alternatively, the use of waste and residual materials as a source of carbon and hydrogen is being investigated. The British Airways GreenSky project planned to produce approximately 1,095 bbl/d of paraffin from household waste, but the project has been discontinued due to the current low oil price. The company Fulcrum BioEnergy plans to use the Sierra BioFuels plant to produce 655 bbl/d of fuel from household waste.

Fischer-Tropsch synthesis in combination with a hydrocracker and product refining have been used and continuously improved for almost 80 years. Therefore, development steps are expected only to a very limited extent. One possible innovation is the research on new catalysts for the Fischer-Tropsch synthesis, which allows the direct use of CO_2 and could thus make the step of synthesis gas production redundant. In addition, processes are currently being developed at the Institute for Micro Process Engineering, KIT, in which the heat generated can be better regulated. This could allow significantly higher conversion rates (Dittmeyer 2017).

Current importance and outlook for 2030/2050

To date, no BTL plants of industrial size exist, but there are first test plants on a smaller scale, such as the Bioliq plant at KIT (Dahmen 2008). Above all, the high biomass consumption limits an industrial-scale plant, so that savings through economies of scale may not be possible. Depending on the plant configuration and the assumptions made, overall efficiencies (based on calorific value) in the range between 30% and 50% for BtL plants have been predicted (Hamelinck 2004, Swanson 2010, Tijmensen 2002). Due to the limited potential, there will hardly be any pure BtL plants in the future either, which is why neither cost nor far-reaching technical developments are to be expected.

Technological parameters

For the following technological and economic parameters, a plant with entrained-flow gasifier, water-gas-shift reactor, Selexol scrubbing and a steam cycle was designed.

The simulated plant has an incoming biomass flow (10 wt.% moisture, e.g., wood chips, residual wood) of 22 t/h . The product flow generated with this is: 2.9 t/h. In addition, it would be possible to generate a further 11 MW of electricity by integrating a steam cycle, in addition to providing all the electricity consumed internally. The usable process heat occurs mainly in the form of steam, which is generated during the cooling of the FT-reactor. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Fuel efficiency	%	37	37	37
Carbon efficiency	%	25	25	25
Potential electricity through steam process	MW	11	11	11
Useable for district heating*	MW	33	33	33

*Heat mainly available in the range of 60 - 220 °C.

Components

The components required for the PBtL process include

- Pyrolysis unit
- Entrained flow gasifier
- Cyclone
- Guard bed
- Filter
- Sorption reactor
- Several heat exchangers
- Water gas shift reactor
- Fischer-Tropsch Reactor
- Hydrocrackers
- Rectification columns
- Pumps
- Compressors/multi-stage compressors
- Cooling unit
- Burners
- (steam turbine/steam cycle)

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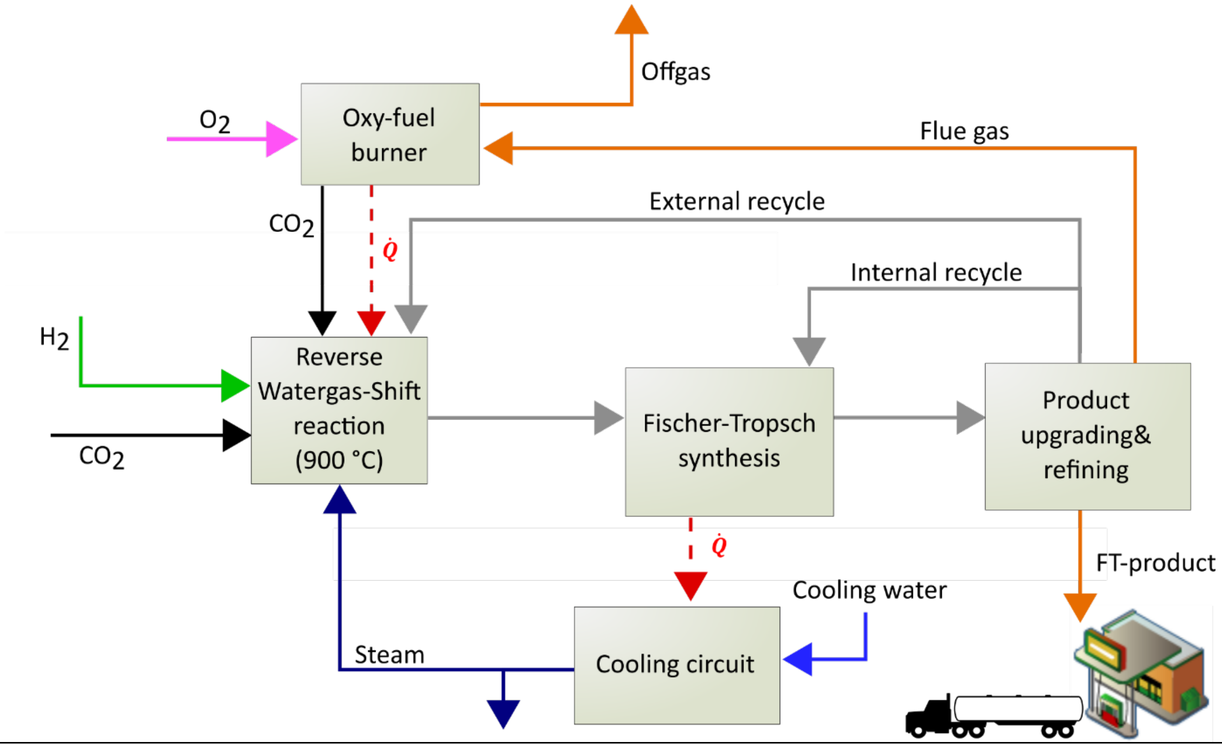
Module 6: Fischer-Tropsch synthesis based on electricity and CO_2 (Power-to-Liquid, FT-PtL)

Technology description

Figure 7: Overview of the FT-PtL process chain



Source: own figure, DLR

The power-to-liquid process consists of CO_2 capture, followed by **synthesis gas generation**, **Fischer-Tropsch synthesis**, a **hydrocracker** and **product preparation/refining**. Depending on the type of synthesis gas generation, a steam cycle is added (Albrecht 2016).

In upstream CO_2 capture, the required carbon is captured from the flue gas of a power plant, an industrial plant or from the air. In addition to the selection criterion of the CO_2 concentration in the waste gas stream described in the chapter on carbon sources, the possibility of using district heating is another factor. If there is a demand for heat at the plant site, excess heat generated in the process can be used to provide district heating. The CO_2 for the PtL process can be separated by physical scrubbing. Examples are separators with Selexol® or Rectisol® as washing liquid. Their advantages are low heat consumption and high separation efficiency (Koytosoumpa 2015, Kuramochi 2011). If there is no need for excess heat, a chemical process should be used for CO_2 capture, as in this case the available heat can be used to dissolve the CO_2 from the scrubbing liquid.

The synthesis gas is produced and conditioned in a reverse water-gas shift reaction (rWGS). In this process, CO_2 and H_2 are converted into CO and water at temperatures up to 1000 °C and pressures up to 50 bar. All further process steps are based on established technologies. In the Fischer-Tropsch synthesis, hydrocarbons are catalytically synthesised at pressures between 20-40 bar and temperatures around 200 - 300 °C. There are two main catalysts used on an industrial scale: cobalt and iron. When operating with cobalt, the operating temperature can be lower than when operating with iron. Furthermore, a higher alkane/alkene ratio is achieved (Klerk 2011). The process is highly exothermic, which is why full conversion in Fischer-Tropsch synthesis is hardly achievable, as the heat cannot be removed from the system quickly enough and the resulting water deactivates the catalyst. The waxes produced in the Fischer-Tropsch synthesis are cracked in the subsequent hydrocracker at about 30 - 80 bar and 300 - 400 °C with the help of additional hydrogen and split into shorter hydrocarbons. The subsequent steps of product separation and refinement must be adjusted according to the desired end product. Unconverted synthesis gas is returned to the FT synthesis or burned in an Oxyfuel burner to provide the required high-temperature heat for the rWGS reactor.

For the life cycle assessment of the technologies used in the process, the materials used for the plant (steel and others) must be taken into account, as well as the catalysts and washing liquids used during operation. The quantities required vary depending on the process management and must therefore be assessed individually for each process.

Technical development trends and development goals

Synthesis gas generation/conditioning by reverse water-gas-shift reaction is still being researched and could possibly be carried out at lower temperatures. This would reduce the energy demand of this process step. In addition, an autothermal operation case is being investigated to simplify the reactor design of the rWGS reactor and thus save costs. Fischer-Tropsch synthesis in combination with a hydrocracker and product refining have been used and continuously improved for almost 80 years. Therefore, development steps are expected only to a very limited extent. One possible innovation is the research on new catalysts for the Fischer-Tropsch synthesis, which allows the direct use of CO_2 and could thus make the step of synthesis gas production redundant. In addition, processes are currently being developed at the Institute for Micro Process Engineering, KIT, in which the heat generated can be better regulated. This could allow significantly higher conversion rates (Dittmeyer 2017).

Current importance and outlook for 2030/2050

Currently, the PtL process does not compete with fossil fuels, as the production costs are significantly higher than the fossil reference. The main cost factor is the electricity price for electrolysis.

Technological parameters

For the following technological and economic parameters, a plant with allothermal reverse water-gas-shift reactor and additional steam cycle was designed. The simulated plant has a hydrogen feed flow of 3.9 t/h and a CO_2 flow after separation of 25.6 t/h. The resulting product flow is 8.2 t/h. Depending on the CO_2 capture, the following values were determined. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

For a system with Selexol® scrubbing:

Technical parameters	Unit	2015	2030	2050
η_{XtL}	%	74	74	74
Carbon efficiency	%	98	98	98
Useable for district heating*	MW	26	26	26

For a plant with MEA scrubbing:

Technical parameters	Unit	2015	2030	2050
η_{XtL}	%	75	75	75
Carbon efficiency	%	98	98	98
Useable for district heating*	MW	0	0	0

*Heat mainly available in the range 60 - 220 °C.

Components

The components required for the PtL process include

- CO_2 separator (Selexol®/Rectisol®/MEA/MDEA/Benfield)
- Several heat exchangers
- Reverse Water-Gas-Shift-reactor
- Fischer-Tropsch reactor
- Hydrocrackers
- Rectification column

- Capacitors
- Pumps
- Compressors/multi-stage compressors
- Cooling unit
- Burners

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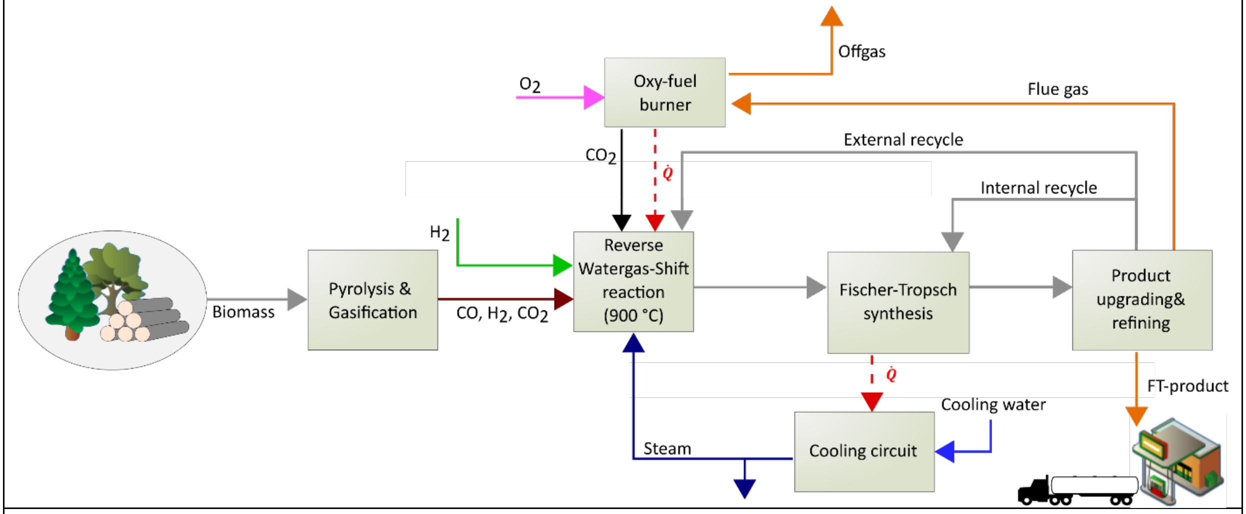
Module 7: Fischer-Tropsch synthesis based on biomass and electricity (Power&Biomass-to-Liquid, FT-PBtL)

Technology description

Figure 8: Overview of the FT-PBtL process chain



Source: own figure, DLR

The Power&Biomass-to-Liquid process is a combination of the PtL and the BtL processes. As in the BtL process, the main components are: pyrolysis and gasification unit followed by synthesis gas conditioning. Finally, the Fischer-Tropsch synthesis, the hydrocracker and the necessary product conditioning/refining. The main difference is the use of additional hydrogen to obtain the desired composition of the synthesis gas. In addition, an Oxyfuel burner provides the required heat for the reverse water-gas-shift reactor (Albrecht 2016).

The advantages of the PBtL process are, on the one hand, that considerably more of the carbon can be used compared to the BtL process and that, in principle, carbon efficiencies of over 95% can be achieved by using an Oxyfuel burner.

If the required hydrogen is obtained by electrolysis, the oxygen produced in the process can be used both for the Oxyfuel burner and in biomass gasification. There are three common types of gasifiers: Fixed bed, fluidised bed and entrained flow gasifiers. For high throughput rates, a fluidised bed or entrained flow gasifier is useful. In addition, the entrained-flow gasifier has the advantage of low unwanted tar and methane production due to very short residence times at operating temperatures of 1000 - 1200 °C. Moreover, this technology is easy to scale and is state of the art at least for coal. On the other hand, an entrained-flow gasifier requires a complex pre-treatment (pyrolysis) of the biomass, as it has to be fed into the gasifier as a pumpable mixture. For smaller plants it may therefore be advantageous to use a fluidised bed reactor (Heidenreich 2015, Molino 2016, Pereira 2012).

The gas produced in the gasifier is then cooled down, for example with water, and cleaned of ash and soot particles before being freed from further impurities (especially HCl, H_2S) by means of centrifugal separators and additional filters or sorption reactors. The clean synthesis gas obtained consists largely of CO, H_2, CO_2 and steam. Depending on the synthesis gas composition obtained, the gas can, after water separation and addition of hydrogen, be directly fed to the Fischer-Tropsch synthesis or be conditioned by using a reverse water-gas shift reactor (rWGS) to achieve a H_2/CO ratio of 2. In an rWGS reactor, CO_2 is converted with H_2 to CO and water at temperatures of up to 1000°C and pressures of up to 50 bar.

All further process steps are based on established technologies. In the Fischer-Tropsch synthesis, hydrocarbons are catalytically synthesised at pressures between 20-40 bar and temperatures around 200-300 °C. There are two main catalysts used on an industrial scale: cobalt and iron. When operating with cobalt, the operating temperature can be lower than when operating with iron. Furthermore, a higher alkane/alkene ratio is achieved (Klerk 2011). The process is highly exothermic, which is why full conversion in Fischer-Tropsch synthesis is hardly achievable, as the heat cannot be removed from the system quickly enough and the resulting water deactivates the catalyst. The waxes produced in the Fischer-Tropsch synthesis are cracked in the subsequent hydrocracker at about 30 - 80 bar and 300 - 400 °C with the help of additional hydrogen and split into shorter hydrocarbons. The subsequent steps of product separation and refinement must be adjusted according to the desired end product. Unconverted synthesis gas is returned to the FT synthesis or is used in an Oxyfuel burner with steam cycle for power generation.

For the life cycle assessment of the technologies used in the process, the materials used for the plant (steel and others) must be taken into account, as well as the catalysts and washing liquids used during operation. The quantities required vary depending on the process management and must therefore be assessed individually for each process.

Technical development trends and development goals

The gasification of biomass is a very energy-intensive process step. The correct process control depends strongly on the composition of the respective biomass. A universally optimal solution will therefore not be found in the foreseeable future; instead, the processes must be selected and optimised for the respective conditions (Tijmensen 2002).

Synthesis gas production by a reverse water-gas shift reaction is still being researched and could possibly be carried out at lower temperatures. This would reduce the energy demand of this process step. In addition, an autothermal mode of operation is being investigated, which could simplify the reactor design of the rWGS reactor and thus enable lower production and operating costs.

Fischer-Tropsch synthesis in combination with a hydrocracker and product refining have been used and continuously improved for almost 80 years. Therefore, development steps are expected only to a very limited extent. One possible innovation is the research on new catalysts for the Fischer-Tropsch synthesis, which allows the direct use of CO_2 and could thus make the step of synthesis gas production redundant. In addition, processes are currently being developed at the Institute for Micro Process Engineering, KIT, in which the heat generated can be better regulated. This could allow significantly higher conversion rates (Dittmeyer 2017).

Current importance and outlook for 2030/2050

So far, neither pure BtL nor PBtL plants of industrial size exist. However, the BtL process route is already being researched in several test plants, e.g., in the Bioliq plant at KIT (Dahmen 2008). The PBtL process is not yet of industrial significance, but it represents a very promising alternative due to the almost fourfold yield of energy carriers with the same biomass/carbon input (Albrecht 2016). If there is a demand for district heating at the selected location, an energy efficiency of 80% can be achieved. To prevent an accumulation of gas impurities, part of the recycled gas is permanently discharged. In case of large plant capacities, it may be advantageous to use this gas in an additional burner and a coupled steam cycle to generate electricity.

Technological parameters

For the following technological and economic parameters, a plant with entrained-flow gasifier, allothermal reverse water-gas-shift reactor and Oxyfuel burner was designed.

The simulated plant has an incoming biomass flow (10 wt.% moisture, e.g., wood chips, residual wood) of 22 t/h and a hydrogen flow of 3.6 t/h. The product flow generated with this is: 11 t/h. It would also be possible to generate a further 6 MW by integrating a steam cycle, in addition to providing all the electricity consumed internally. The usable process heat occurs mainly in the form of steam, which is generated during the cooling of the FT reactor. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Fuel efficiency	%	62	62	62
Carbon efficiency	%	98	98	98
Electricity through steam process	MW	6	6	6

Useable for district heating*	MW	32	32	32

*Heat mainly available in the range 60 - 220 °C.

Components

The components required for the PBtL process include

- Pyrolysis unit
- Entrained flow gasifier
- Cyclone
- Guard bed
- Filter
- Several heat exchangers
- Reverse Water-Gas-Shift-reactor
- Fischer-Tropsch reactor
- Hydrocrackers
- Rectification columns
- Pumps
- Compressors/multi-stage compressors
- Cooling unit
- Burners

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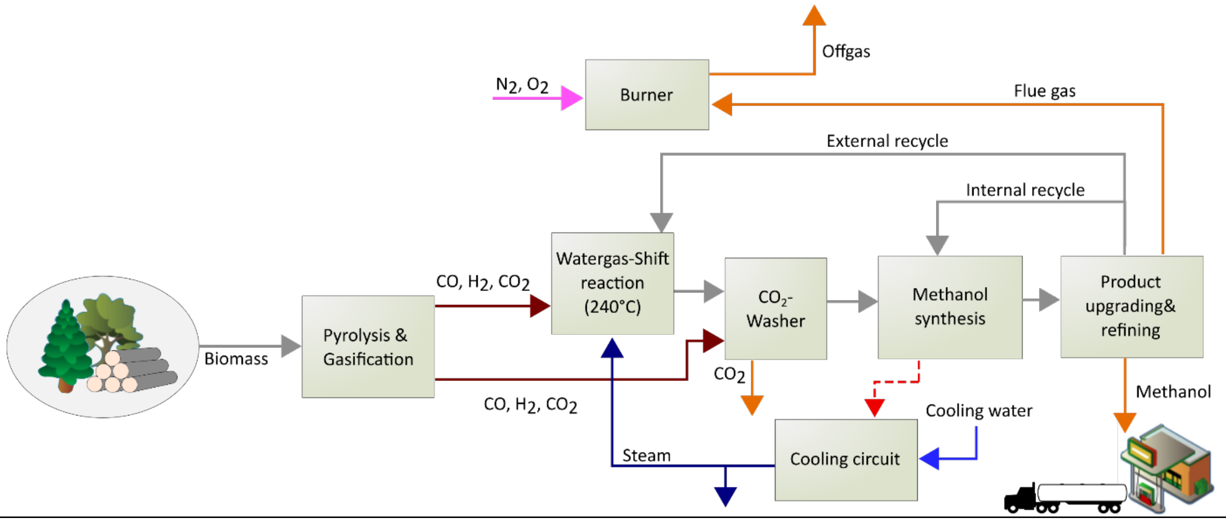
Module 8: Methanol synthesis based on biomass (Biomass-to-Liquid, MS-BtL)

Technology description

Figure 9: Overview of the BtL process chain for methanol production



Source: own figure, DLR

In the BtL process, biomass is first dried and processed and then gasified in a gasification unit. The resulting gas is then prepared for methanol synthesis through gas purification and gas conditioning steps and then the methanol is concentrated in a separation column.

There are three common gasifier types: Fixed bed, fluidised bed and entrained flow gasifiers. For high throughput rates a fluidised bed or entrained flow gasifier is useful. In addition, the entrained flow gasifier has the advantage of a low faulty production of tar and methane due to the very short residence times at operating temperatures of 1000 - 1200 °C. Furthermore, this technology is easy to scale and is state of the art at least for coal. On the other hand, an entrained-flow gasifier requires a complex pre-treatment (pyrolysis) of the biomass, as it has to be fed into the gasifier as a pumpable mixture. For smaller plants it may therefore be advantageous to use a fluidised bed reactor (Heidenreich 2015, Molino 2016, Pereira 2012).

The gas produced in the gasifier is then cooled with water and cleaned of ash and soot particles, before it is freed from further impurities (especially HCl, H_2S) by means of centrifugal separators and filters or sorption reactors. The synthesis gas thus obtained consists largely of CO, H_2, CO_2 and steam. Depending on the composition of the synthesis gas received via gasification, the gas can either be fed directly to the methanol synthesis after water separation or conditioned in a water-gas shift reactor (WGS) to achieve a ratio of $H_2/(2\,CO + 3\,CO_2) = 1.05$. In the WGS reactor, CO and water are converted to CO_2 and H_2 at temperatures of up to 300 °C and pressures of up to 50 bar. Subsequently, the excess CO_2 is separated in a CO_2 scrubber. The separation methods used depend on the existing heat market or electricity costs. In principle, a Rectisol® scrubber for CO_2 capture is useful in methanol production, as it uses methanol as a washing agent.

Methanol synthesis is carried out at 240 - 260 °C, pressures up to 100 bar and usually with a copper catalyst and a recycling factor of 4 to 7. This means that unreacted educts are recycled and fed back into the reactor. The recycling ratio describes the ratio of the refluxed stream to the fresh feed from synthesis gas conditioning (Bartholomew 2006).

For the life cycle assessment of the technologies used in the process, it is necessary to consider the materials used in the process design (steel and others) as well as the catalysts and washing liquids used during operation. The quantities required vary depending on the process design and must therefore be assessed individually for each process.

Technical development trends and development goals

The research focus for biomass-to-liquid technology is the further development of biomass gasifiers and gas cleaning as well as the demonstration of the overall process (Hamelinck 2004, Swanson 2010, Tijmensen 2002).

The gasification of biomass represents a very energy-intensive process step. The correct process control depends strongly on the composition of the respective biomass. A universally optimal solution will therefore not be found in the foreseeable future. Instead, the processes must be selected and optimised for the respective framework conditions (Tijmensen 2002).

Gas purification is very costly, especially due to the different compositions of the individual biomasses, as high fluctuations in the composition of the pyrolysis gas must be expected.

The synthesis of methanol or DME is a fundamental process in the chemical industry and is therefore state of the art. The influence of the $H_2/CO/CO_2$ ratio in the synthesis gas is currently being investigated in several studies (Chen 2016, Ateka 2017, Kuznetsov 2009).

Current research focuses on the investigation of CO_2-active catalysts to skip the reverse water-gas-shift reaction. Two-stage reactor concepts are also being investigated to enable direct processing to dimethyl ether (DME), which can be used as a drop-in for conventional fuels and reduce their emissions.

Current importance and outlook for 2030/2050

At present, the BtL process does not compete with the production of methanol from fossil raw materials, as the production costs are significantly higher. The technical implementation depends on the development of biomass gasification and the subsequent synthesis gas conditioning.

Technological parameters

A plant with an incoming biomass flow (10 wt.%) of 22 t/h was designed for the following technical and economic parameters. The methanol flow generated with this is 6.5 t/h. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
η_{BtL}	%	36	36	36
$\eta_{energetic^*}$	%	42	42	42
η_C	%	30	30	30
Electricity through steam process	MW	6	6	6
District heating	MW	14	14	14

*maximum achievable efficiency if heat and electricity market exists; otherwise η_{BtL} applies.

Components

The components required for the BtL process include

- Biomass drying unit
- Entrained flow gasifier
- Gas cleaning (Rectisol)
- Several heat exchangers
- Water-Gas-Shift-reactor
- Methanol synthesis
- Separation column
- Pumps
- Compressors/multi-stage compressors
- Burners
- Gas turbine/steam turbine/steam cycle

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A. Ateka, P.Pérez-Uriarte, M. Gamero (2017). A comparative thermodynamic study on the CO_2 conversion in the synthesis of methanol and of DME.

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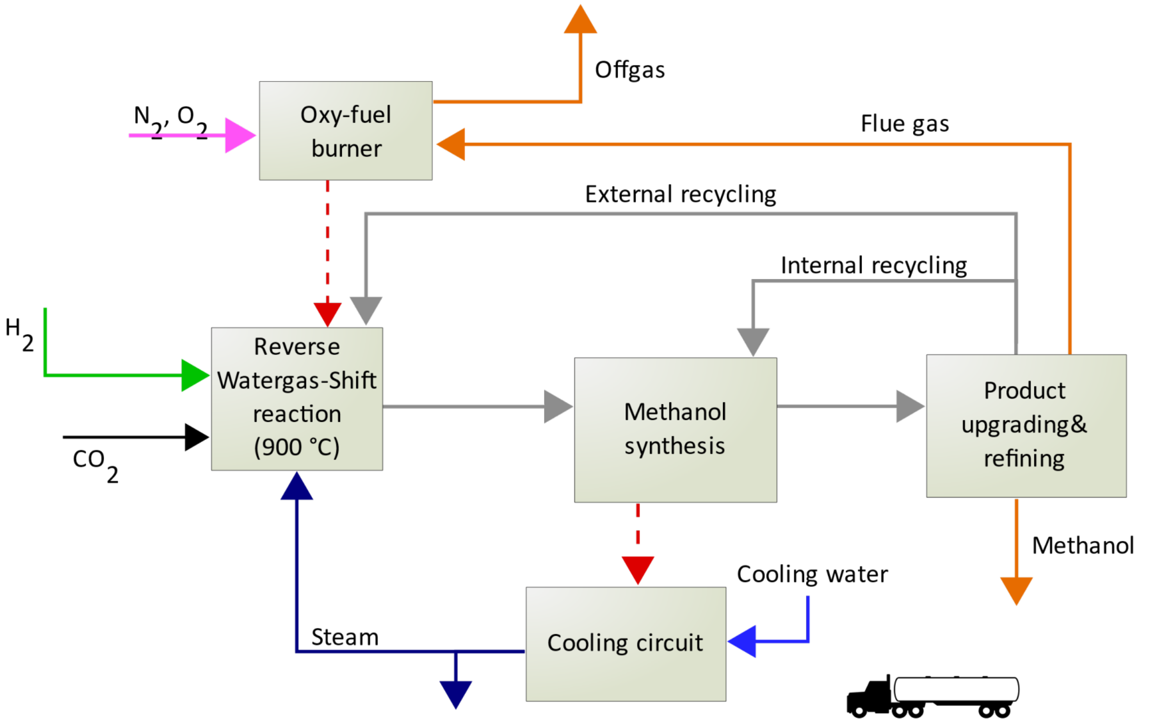
Y. K. Salkuyeh, T. A. Adams II (2014). A new power, methanol, and DME polygeneration process using integrated chemical looping systems

Module 9: Methanol synthesis based on electricity and CO_2 (Power-to-Liquid, MS-PtL)

Technology description

Figure 10: Overview of the PtL process chain for methanol production



Source: own figure, DLR

The power-to-liquid process consists of an upstream CO_2 capture, followed by **synthesis gas generation**, **methanol synthesis** and a **separation column**. In CO_2 capture, the required carbon is extracted from the flue gas stream of a power plant, an industrial plant or from the air. In addition to the selection criterion of the CO_2 concentration in the waste gas stream described in the chapter on carbon sources, the possibility of using district heating is another factor. If there is a demand for heat at the site of the installation, the excess heat generated in the process can be used in the form of district heating. The CO_2 for the PtL process will then be separated via physical scrubbing. Examples are separators with Selexol® or Rectisol® as washing liquid. Their advantages are low heat consumption and high separation efficiency (Koytosoumpa 2015, Kuramochi 2011). If there is no need for excess heat, a chemical process should be used for CO_2 capture, as in this case the available heat can be used to dissolve the CO_2 from the scrubbing liquid. Suitable washing liquids are MEA, MDEA or K_2CO_3 (Urech 2013, Schäffler 2013).

The synthesis gas is produced and conditioned in a reverse water-gas shift reaction (rWGS). In this process, CO_2 and H_2 are converted into CO and water at temperatures up to 1000°C and pressures up to 50 bar. After water separation, excess CO_2 is separated with the aid of a CO_2 scrubber. In principle, it is useful to use a Rectisol scrubber for CO_2 capture in the production of methanol, as this uses methanol as a washing agent.

The methanol synthesis is operated at 40 - 260 °C, pressures up to 100 bar and usually with a copper catalyst and a recycling factor of 4 to 7 (unreacted educts are fed back into the reactor). The recycling ratio describes the ratio of the refluxing stream to the educt stream from synthesis gas conditioning (Bartholomew 2006).

For the life cycle assessment of the technologies used in the process, it is necessary to consider the materials used in the process design (steel and others), as well as during operation, the catalysts and washing liquids used. The quantities required vary depending on the process design and must therefore be assessed individually for each process.

Technical development trends and development goals

Synthesis gas generation/conditioning by reverse water-gas-shift reaction is still being researched and could possibly be carried out at lower temperatures. This would reduce the energy demand of this process step. In addition, an autothermal mode of operation is being investigated which could simplify the reactor design of the rWGS reactor and thus make lower production and operating costs possible.

The synthesis of methanol or DME represents a fundamental process in the chemical industry and is therefore state of the art. The influence of the $H_2/CO/CO_2$ ratio in the synthesis gas is currently being investigated in several experimental and kinetic studies (Chen 2016, Ateka 2017, Kuznetsov 2009). Current research focuses on the investigation of CO_2-active catalysts to skip the step of the reverse water-gas-shift reaction. In addition, two-stage reactor concepts are being investigated to enable direct further processing to dimethyl ether (DME), which can serve as a drop-in for conventional fuels and reduce their emissions.

Current importance and outlook for 2030/2050

In 2012, 58 million tonnes of methanol were produced worldwide using synthesis gas consisting of carbon monoxide and hydrogen (IEA 2013). For methanol synthesis with regeneratively produced hydrogen and using CO_2, two relevant and technically similar plants can currently be identified which use different CO_2 sources:

- A commercial plant operated by Carbon Recycling International in Iceland with CO_2 from geothermal sources and an annual capacity of 5 million litres. (CRI 2018)
- A research plant in Lünen, Germany using CO_2 from flue gases of a hard coal-fired power plant.

At present, the PtL process only competes with the production of methanol from fossil raw materials under very narrowly defined conditions (as is the case with CRI in Iceland), as the production costs are significantly higher. The main cost factor is the electricity price for electrolysis.

Technological parameters

For the following technological and economic parameters, a plant with allothermal reverse water-gas-shift reactor and additional steam cycle was designed.

The simulated plant has a hydrogen feed stream of 4.8 t/h and a CO_2 stream after separation of 33 t/h. The resulting methanol product flow is 20.5 t/h.

A complete list of technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
$\eta_{XtMethanol}$	%	84	84	84
$\eta_{energetic*}$	%	86	86	86
η_C	%	93	93	93
Useable for district heating (medium pressure steam)	MW	3	3	3

*maximum achievable efficiency, if heat market available. If not, the XtL efficiency applies.

Components

The components required for the PtL process include

- CO_2 separator (Selexol®/Rectisol®/MEA/MDEA/Benfield)
- Several heat exchangers
- Reverse Water-Gas-Shift-reactor
- Methanol synthesis
- Separation columns
- Pumps

- Compressors/multi-stage compressors
- Cooling unit
- Burners
- (steam turbine)

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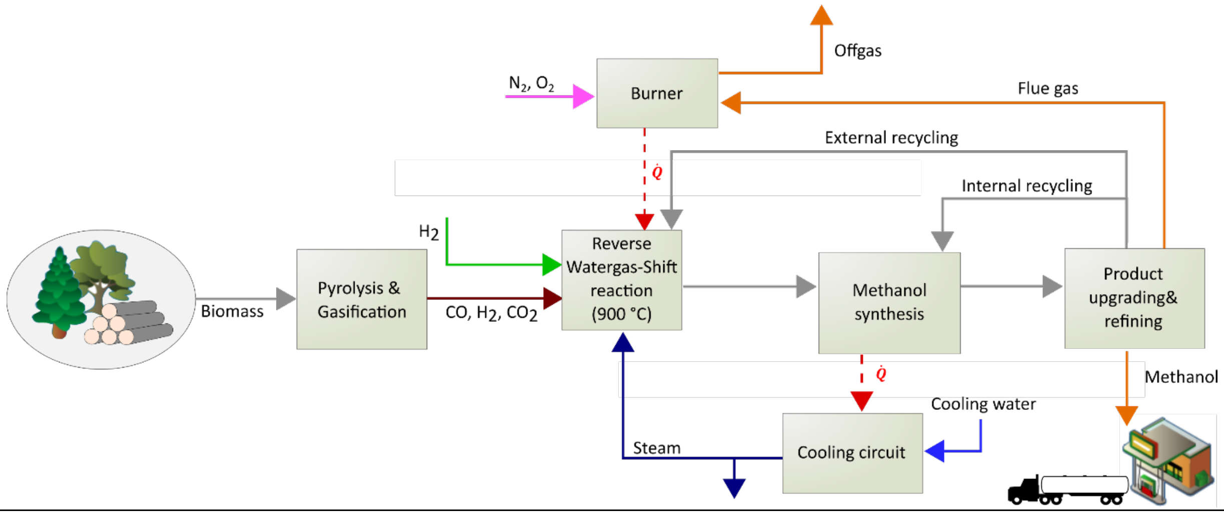
Y. K. Salkuyeh, T. A. Adams II (2014). A new power, methanol, and DME polygeneration process using integrated chemical looping systems

CRI - Website of the company Carbon Recycling International URL: http://carbonrecycling.is Retrieved on 19.6.2018

Module 10: Methanol synthesis based on biomass and electricity (Power&Biomass-to-Liquid, MS-PBtL)

Technology description

Figure 11: Overview of the PBtL process chain for methanol production



Source: own figure, DLR

The Power&Biomass-to-Liquid process is a combination of PtL and BtL processes. As in the BtL process, the main components are: **dryer** and **gasification unit** followed by **synthesis gas conditioning** for **methanol synthesis** and a **separation column**. The main difference is the use of additional hydrogen to obtain the desired composition of the synthesis gas. In addition, an Oxyfuel burner provides the heat required for the reverse water-gas shift reactor (rWGS) (Albrecht 2016).

One advantage of the PBtL process compared to the BtL process is that considerably more of the carbon fed in can be used. If the required hydrogen is obtained by electrolysis, the oxygen produced can be used both for the oxyfuel burner and in biomass gasification.

There are three common gasifier types: Fixed bed, fluidised bed and entrained flow gasifiers. For high throughput rates a fluidised bed or entrained flow gasifier is useful. In addition, the entrained-flow gasifier has the advantage of a low faulty production of tar and methane due to the very short residence times at operating temperatures of 1000 - 1200 °C. Moreover, this technology is easy to scale and is state of the art at least for coal. On the other hand, an entrained-flow gasifier requires a complex pre-treatment (pyrolysis) of the biomass, as it has to be fed into the gasifier as a pumpable mixture. For smaller plants it may therefore be advantageous to use a fluidised bed reactor (Heidenreich 2015, Molino 2016, Pereira 2012).

The gas produced in the gasifier is then cooled down, for example with water, and cleaned of ash and soot particles before being freed from further impurities (especially HCl, H_2S) by means of centrifugal separators and additional filters or sorption reactors. The synthesis gas thus obtained consists largely of CO, H_2, CO_2 and steam. Depending on the composition of the synthesis gas, the gas can either be fed directly to the methanol synthesis after water separation and the addition of hydrogen, or it can be conditioned by using a reverse water-gas-shift reactor (rWGS) to achieve a ratio of $H_2/(2\ CO + 3\ CO_2) = 1.05$. In the rWGS reactor CO_2 and H_2 are converted to CO and water at temperatures up to 1000 °C and pressures up to 50 bar. At pressures above 10 bar, additional water vapour must usually be fed into the reactor as otherwise coking may occur. This can also inhibit the formation of methane. The methanol synthesis is operated at 240 - 260 °C, pressures up to 100 bar and usually with a copper catalyst and a recycling factor of 4 to 7. This means that unreacted educts are recycled and fed back into the reactor. The recycling ratio describes the ratio of the refluxed stream to the fresh feed from synthesis gas conditioning (Bartholomew 2006). A part of the recycled gas is led to the rWGS reactor to prevent an accumulation of CO_2 in the overall system.

For the life cycle assessment of the technologies used in the process, it is necessary to consider the materials used in the process design (steel and others) as well as the catalysts and washing liquids used during operation.

The quantities required vary depending on the process design and must therefore be assessed individually for each process.

Technical development trends and development goals

The gasification of biomass represents a very energy-intensive process step. The correct process control depends strongly on the composition of the respective biomass. A universally optimal solution will therefore not be found in the foreseeable future; instead, the processes must be selected and optimised for the respective conditions (Tijmensen 2002).

Gas purification is very costly, especially due to the different compositions of the individual biomasses, as high fluctuations in the composition of the pyrolysis gas must be expected.

Synthesis gas production by a reverse water-gas shift reaction is still being researched and could possibly be carried out at lower temperatures. This would reduce the energy demand of this process step. In addition, an autothermal mode of operation is being investigated which could simplify the reactor design of the rWGS reactor and thus enable lower production and operating costs.

The synthesis of methanol or DME represents a fundamental process in the chemical industry and is therefore state of the art. The influence of the $H_2/CO/CO_2$ ratio in the synthesis gas is currently being investigated in several experimental and kinetic studies (Chen 2016, Ateka 2017, Kuznetsov 2009).

Current research focuses on the investigation of CO_2-active catalysts in order to skip the step of the reverse water-gas-shift reaction. Two-stage reactor concepts are also being investigated to enable direct processing into dimethyl ether (DME), which can be used as a drop-in for conventional fuels and reduce their emissions.

Current importance and outlook for 2030/2050

At present, the PBtL process does not compete with the production of methanol from fossil raw materials, as the production costs are significantly higher. The main cost factor is the electricity price for electrolysis.

The increased yield of energy carriers with the same biomass input means a significant advantage over pure BtL processes (Albrecht 2016).

Technological parameters

For the following technological parameters, a plant with pressure-loaded entrained-flow gasifier, allothermal rWGS reactor and a recycling factor of 5 was designed.

The simulated plant has an incoming biomass flow (10 wt.%) of 22 t/h and a hydrogen flow of 2.4 t/h. The methanol flow generated with this is 21 t/h. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
η_{XtL}	%	67	67	67
$\eta_{energetic}$	%	79	79	79
η_C	%	88	88	88
Electricity through steam process	MW	3	3	3
Useable for district heating**	MW	21	21	21

*maximum achievable efficiency, if heat market available. If not, the XtL efficiency applies.
**Heat mainly available in the range 60 - 150 °C

Components

The components required for the PBtL process include

- Pyrolysis unit
- Entrained flow gasifier

- Cyclone
- Guard bed
- Filter
- Several heat exchangers
- Reverse water-gas-shift-reactor
- Methanol synthesis
- Separation columns
- Pumps
- Compressors/multi-stage compressors
- Burners
- Steam turbine/ steam cycle

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2.1.3 Production of gaseous hydrocarbons

The modules on the gaseous hydrocarbon biomethane were compiled mainly on the basis of the project Biogas Gesamtbewertung der JOANNEUM RESEARCH (Bleyl-Androschin 2011), which is funded by the Austrian Research Promotion Agency, and the DBFZ Report No.26 (Billig 2016) as the latest study relating to Germany. These and other sources are listed in the respective fact sheets. The technologies in the supply chain from biogas production to biomethane are presented in one profile for biomass fermentation and five profiles for biogas upgrading to biomethane.

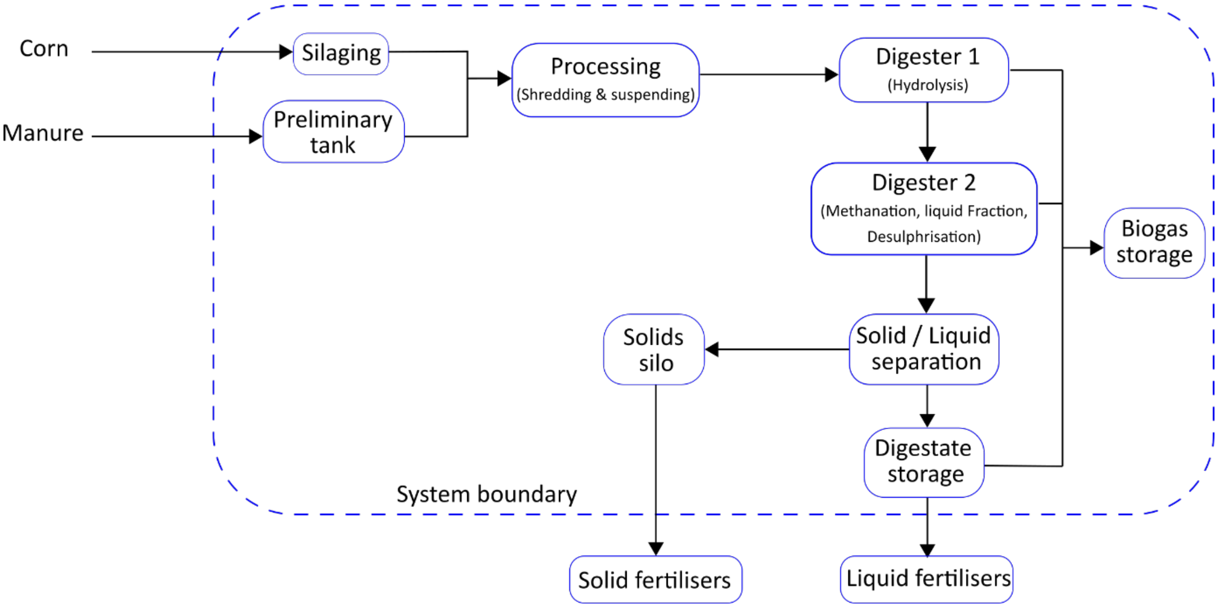
The second technology considered in this chapter is the production of synthetic natural gas (SNG) from CO_2 and H_2. The data for this process are taken from the literature on the few demonstration and pilot scale plants.

Biomass fermentation
Module 11: Biogas from agricultural raw and residual materials
Module 12: Biogas from organic waste

Technology description

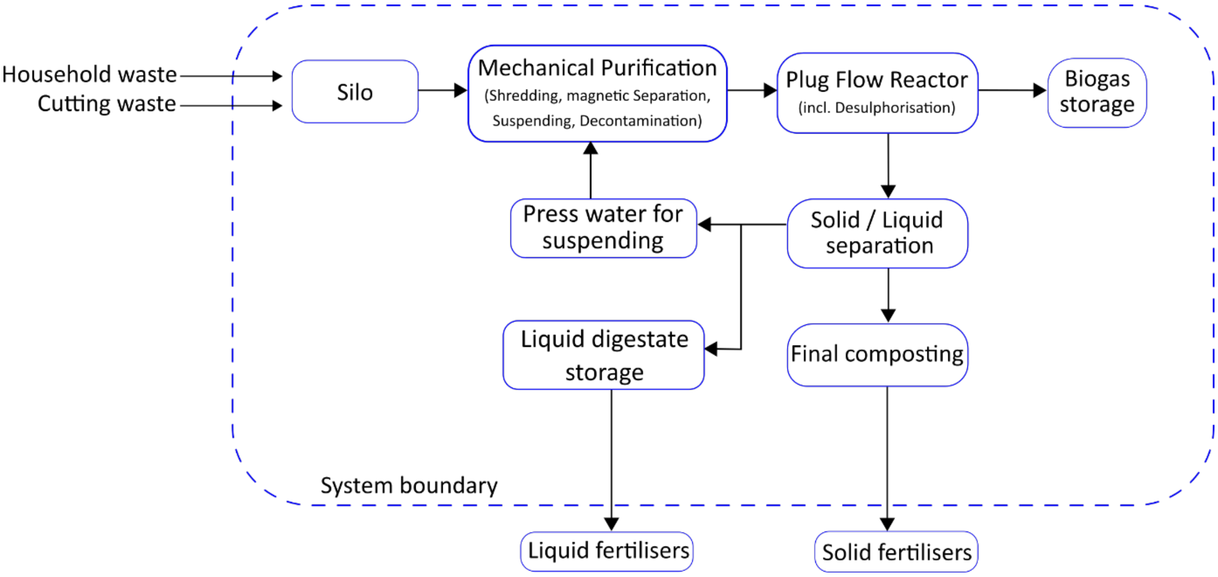
The system boundary of this module begins with the delivery of the biomass to the biogas plant (BGP) and ends with the leaving of the raw biogas and the fermentation residue. The module comprises four main process steps: **intermediate storage** and **processing of the biomass, biogas production** in the fermenter, **intermediate gas storage**, and the **processing and storage of the fermentation residue**.

Figure 12: Process chain of biogas production from agricultural substrates



Source: own figure, JOANNEUM RESEARCH

Figure 13: Process chain of biogas generation from biowaste



Source: own figure, JOANNEUM RESEARCH

After delivery, the biomass is temporarily stored. Cultivated biomass such as maize is crushed and ensiled to preserve the substrate and increase the methane yield of the substrate in the fermenter. Ensiling is associated with silage losses; as a rule, 12% is used (Dunkelberg 2015). The intermediate storage of liquid manure/manure or organic waste is carried out in a preliminary pit or in a bunker, depending on the solids content. The preparation of the biomass in the BGP is used to shred, mix and homogenise the substrate (especially in the case of conventional mixtures of substrates, e.g., maize silage with liquid manure, residue mix) in order to make it pumpable or to enable optimum mixing of substrate and microorganisms in the fermenter.

The process of biogas production in the fermenter is a sequence of 4 phases in which the substrate (complex carbohydrates, proteins, fats) is continuously degraded in the absence of oxygen into simpler organic compounds up to methane and carbon dioxide, the main components of biogas. Different groups of micro-organisms are involved in the individual phases of the degradation process, which work optimally in different environments (mainly determined by pH value and temperature). A distinction is made here between the first two phases of hydrolysis and acidogenesis (pre-acidification, pH value 5.2 to 6.3) and the phases acetogenesis and methanogenesis (methane formation, pH value 6.5 to 8) (FNR 2016). Often two-stage plants are operated which spatially separate the conversion phases hydrolysis and methanogenesis in two containers (Postel 2009). With regard to the temperature ranges in the fermenter, one speaks of psychrophilic (<25°C), mesophilic (30-42°C) and thermophilic (48-55°C) BGP. Most BGP are operated in the mesophilic range, thermophilic BGP are primarily used when hygienisation of the substrate is required due to harmful germs (especially for organic municipal, commercial and industrial residues).

Another distinguishing feature of fermenters is the solid content of the substrate. The distinction between liquid and solid fermentation is often made with the terms wet or dry fermentation. In any case, the microbiological process can only take place in the aqueous phase. The differentiation is therefore based on the pumpability of the substrate. As a rule of thumb, a limit of 15 ± 5 mass% is valid for the pumpability (FNR 2016). For agricultural raw and residual materials, continuous wet fermentation in stirred reactors is predominantly used in Germany, for biowaste from separate collection the continuous plug-flow reactor, and for commercial and industrial organic waste predominantly continuous wet fermentation (Daniel-Gromke 2017).

Depending on the substrate, the biogas yield per tonne of fresh mass used as well as the methane content in the raw biogas varies over a wide range. Maize silage yields 180-220 Nm³ biogas per tonne of fresh mass used, with a methane content of approx. 52%. Organic waste yields 100-140 Nm³ biogas per tonne of fresh mass used with a methane content of approx. 60%. On the lower end, pig slurry yields with approx. 10-30 Nm³ biogas per tonne of fresh mass used and a methane content of approx. 60%.

The raw biogas mainly consists of 50 - 75% methane (CH_4), 25 - 16% carbon dioxide (CO_2), 2 - 70% water vapour (H_2O), < 22% oxygen (O_2), < 22% nitrogen (N_2), < 8% ammonia (NH_3) and < 8% hydrogen sulphide (H_2S) (FNR 2013). In particular, hydrogen sulphide and water vapour must be removed in order to prevent corrosion in the gas-carrying parts of the plant and not to have a negative impact on the subsequent BGPC processes for biomethane. In this module a chemical coarse desulphurisation takes place by adding ferric chloride in the fermenter (170 g/t substrate) (Dunkelberg 2015). Processes for fine desulphurisation and drying are described in the BGPA modules.

The biogas is produced in real operation with fluctuating quantities and requires a gas buffer storage for subsequent treatment with a constant gas quantity (max. 1-2 daily productions are usual). For this purpose, foil bonnets on fermenters or fermentation residue stores are used in the low-pressure range, or foil cushions in own buildings, less frequently fixed high-pressure stores.

The third step of the fermentation residue storage process serves as a time buffer between the accumulation of the fermentation residue and the optimal time for the application of the fermentation residue to the areas to be fertilised. According to the German ‘Düngeverordnung’ (BMEL 2017), the fermentation residue storage facility must have a storage capacity of at least 6 months (or of 9 months if no farm-owned fertiliser application areas are available). The fermentation residue store has a gas collection facility for the biogas produced in the post-fermentation process. In certain cases, depending on the subsequent use, available application areas and available storage capacity, solid components are separated from the liquid fraction (solid-liquid separation). This concerns especially waste fermentation plants without company-owned fertiliser application areas.

Against the background of the diversity of possible design variants of biogas plants, the reference BGP for this module was defined. The reference BGP are basically based on the economically necessary size of the later BGPA (see BGPA modules) and not on that of a pure CHP operation. The selection was made on the basis of the current plant stock of BGPA and BGPA in Germany (Daniel-Gromke 2017) as well as consistently available technical, ecological and economic data on biogas production and on the five BGPA technologies investigated in (Bleyl-Androschin 2011), (Billig 2016), (Dunkelberg 2015) and (Beil 2017).

The first reference BGP is an agricultural BGP with use of agricultural raw and residual materials, which is operated in line with the majority of such plants in Germany as two-stage (hydrolysis, methanisation) continuous wet fermentation in the mesophilic temperature range (FNR 2012), (Daniel-Gromke 2017). The fermenter type is a continuous stirred reactor. After the first stage, the fermentation residue enters a solid-liquid separation. The liquid fraction is then conveyed to the second fermenter for methanisation, the solid fraction is bunkered. After the second fermenter, the liquid fermentation residue passes into the fermentation residue storage. The substrate mix and the plant size are based on the plant stock of agricultural biogas plants in Germany (Daniel-Gromke 2017). A mix of 60% maize silage and 40% pig manure is used as substrate. The biogas output is 1.400 Nm^3/h with a methane content of 52.5%.

The second reference BGP is a bio-waste BGP. The substrate is composed of 90% household organic waste and 10% municipal green waste. The biowaste is processed wet mechanically to remove impurities and produce a suspension. The fermentation technology used is a continuous plug-flow reactor in the thermophilic temperature range. After the reactor, a solid-liquid separation takes place, followed by post-rotting for the solid fraction. The biogas output is 1.400 Nm^3/h with a methane content of 58.7%.

Both reference BGP require power and heat during operation. The heat is provided by a gas boiler on site. The gas boiler is operated with biomethane and lean gas from the BGPU. Electricity is drawn from the grid. Emissions from the operation of a BGPA are especially methane losses in the gas-bearing parts, which are estimated at 1% of the methane produced (Dunkelberg 2015). Methane emissions from gas storage facilities are limited to 0.1% of methane under EEG 2012. Further emissions are produced during operation of the gas boiler (CO_2, NO_X, CH_4).

Technical development trends and development goals

Developments in the field of BGP are aimed, on the one hand, at the technological optimisation of the BGP itself and, on the other hand, at an optimised integration of a BGP into the overall value chain. Development topics for BGP technology are the optimisation of the fermentation process (e.g., through new efficient bacteria, which contribute to a higher biogas yield, but also through better process controlling) and the reduction of the own energy demand of electricity and heat (e.g., energy-saving agitators, heating through heat recovery). Building on the use of agricultural raw materials and residues, there is technical development potential in the use of residues as a substrate, in particular biowaste from municipal, commercial and industrial sources and straw (IFEU 2017). A further development trend is the increase in the value added from biomass, on the one hand under the term fermentation residue refinement, with which fertilisers are precisely adjusted in terms of nutrients and heavy metals in multi-stage plants, and on the other hand within the framework of a biorefinery, in which BGP represents only part of a value-added chain with new products.

The technological parameters were left unchanged for 2030 and set for 2050 on the basis of the following assumptions: The methane yield increases by 10% due to new bacteria, the auxiliary energy input for electricity and heat decreases by 10% due to more efficient technologies.

Current importance and outlook for 2030/2050

In Germany, out of approx. 8,700 BGP (stock at the end of 2016), approx. 8,200 are agricultural BGP (of which 560 are small-scale liquid manure plants with <75 kWel, 900 to 1,000 plants with >80% liquid manure/solid manure content), 335 are waste fermentation plants (of which 135 with a waste content > 90%) and 196 are BGPA. 61% of the biogas is used for electricity generation, 31% for heat generation, 1% for biomethane production as vehicle fuel and 31% is flared. In 2016, the share of electricity generated with biogas will amount to 17,2% of renewable electricity production in Germany (Liebetrau 2017).

Since the EEG remuneration period would end for the majority of existing plants from 2023/2024 onwards, the EEG 2017 provides for follow-up support for a further 10 years. However, the EEG 2017 aims to increase competition by putting a fixed amount of biogas electricity out to tender annually and awarding contracts to the cheapest suppliers. In addition, flexible plants that can offer on the control energy market become more economically interesting. BGP technology therefore has innovation potential in the short term in the direction of "flexible electricity supply" and in the medium term for the production of new intermediate products for material-energy use, the research into which is still in its infancy in some cases. Based on current knowledge, the medium term will therefore see less of a further expansion of biogas plants and more of a targeted conversion of existing plants (larger CHPs, flexibilization, BGPU) (Thrän 2015). Of course, location factors such as proximity to the corresponding consumers of the energy carriers (gas grid for methane, heating network for heat from CHPs) are also decisive in this context.

In order to be competitive in the future, BGP operators will increasingly demand cheaper substrates. The EEG 2017 also limits the use of maize to 50% (to 44% from 2021). On the substrate side, the opportunities for BGP in future therefore lie in the increased use of residual materials from the municipal, commercial and industrial sectors.

Technological parameters

Reference BGP agricultural raw and residual materials (see technology description) according to (Billig 2016). A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Operating hours	h/a	8,400	8,400	8,400
Biogas volume output	Nm³/h	1,400	1,400	1,400
Methane volume output	Nm³/h	770	770	808
Maize silage input	t/a FM	61,740	61,740	61,740
Pig manure input	t/a FM	36,750	36,750	36,750
Auxiliary energy electricity	MJ/Nm	0.54	0.54	0.49
Auxiliary energy heat (mesophilic)	MJ/Nm	1.31	1.31	1.18

Substrates mix of 60% maize silage, 40% pig manure; FM=fresh matter

Reference BGP residuals (see technology description), interpretation based on (Billig 2016)

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Operating hours	h/a	8,400	8,400	8,400
Biogas volume output	Nm³/h	1,400	1,400	1,400
Methane volume output	Nm³/h	840	840	924
Bio-waste input	t/a FM	96,470	96,470	96,470
Municipal green waste input	t/a FM	10,530	10,530	10,530
Auxiliary energy electricity	MJ/Nm	1.9	1.9	1.7
Auxiliary energy heat (thermophilic)	MJ/Nm	1.7	1.7	1.5

Substrates mix: 90% organic waste, 10% green waste; FM=fresh mass

Components

The reference BGP for the use of agricultural raw materials and residues consists of

- Pre-pit (liquid manure)
- Ensiling (Nawaros)
- Fermenter 1st stage (continuous stirred reactor)
- Fermenter 2nd stage (continuous stirred reactor)
- Solid-liquid separator

- Gas Storage
- Fermentation residue storage
- Gas flare

The reference BGP for the use of residual materials (biowaste) consists of

- Bunker in Halle
- Wet mechanical processing Bio-waste
- Fermenter (Continuous plug-flow reactor)
- Gas Storage
- Solid-liquid separator
- Fermentation residue storage
- post-rotting, including exhaust air collection and treatment
- Gas flare

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Biogas treatment
Module 13: Pressure swing adsorption (PSA)
Module 14: Pressure water scrubbing (PWS)
Module 15: Polyglycol scrubbing (Gensorb®)
Module 16: Membrane separation process
Module 17: Amine scrubbing

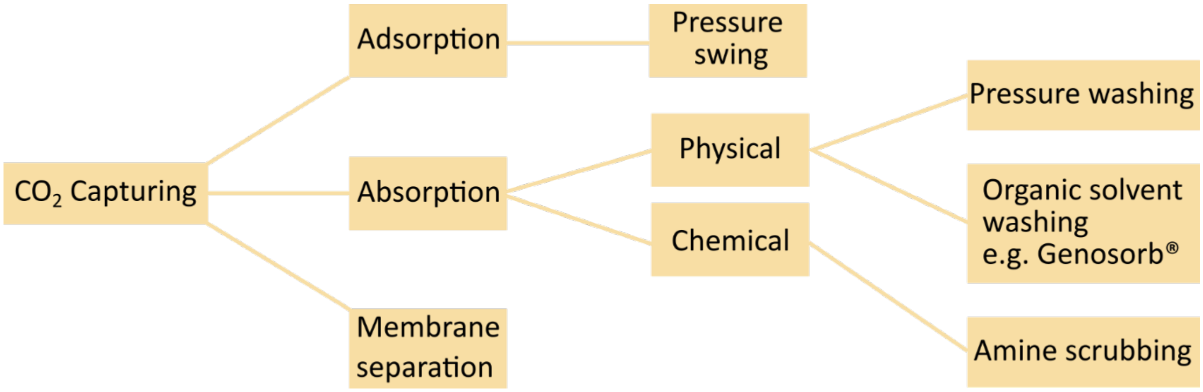
Technology description

Biogas upgrading serves to separate the methane from the other biogas components such as water vapour, carbon dioxide, hydrogen sulphide, ammonia and other gases. The system boundary of this module starts with the delivery of the raw biogas from the biogas plant (BGP) for biogas upgrading and ends before the intermediate storage or the injection of the biomethane into the natural gas grid.

The CO_2 captured during treatment is usually released into the atmosphere today. In future, it can be used for the production of PtX energy carriers.

The following figure provides an overview of the five biogas upgrading processes that are already in market application: **Pressure swing adsorption**, **pressurised water scrubbing**, **polyglycol scrubbing**, **membrane process** and **amine scrubbing**. The processes described here are closely related to the large-scale CO_2 capture processes in the industrial and power plant sector (Chapter 2.2.3).

Figure 14: Overview of possible CO_2 capture paths



Source: FNR 2014

Pressure swing adsorption (PSA) is an adsorptive biogas treatment process. Adsorption is the accumulation of gas components (here: CO_2) on the surface of solids (adsorbents). Activated carbons, zeolites or carbon molecular sieves can be used as adsorbents. The plant component is called an adsorber. High pressures and low temperatures favour the adsorption process of CO_2. Therefore, the biogas is compressed before the adsorbers, heated and then cooled again. At the same time, water is also removed from the gas by condensation drying. The hydrogen sulphide must also be removed before the adsorption cycle. This step is carried out in a fine desulphurisation process with catalytic oxidation or impregnated activated carbon as the state of the art. For regeneration, the loaded adsorbents are expanded to almost ambient pressure. During this process, large quantities of methane are still produced. In order to reduce the methane slip and to increase the efficiency of the process, this gas flow is fed back to the compressor on the suction side. In a final step, a vacuum pump is used to reduce the pressure to negative pressure. In this process, the previously adsorbed CO_2 is desorbed and fed to a lean gas aftertreatment, as small quantities of methane are still present. The lean gas is converted into heat in a burner and is used e.g., to cover the heat demand of the fermenter of the BGP. A maximum permitted methane slip of 0,2% can be maintained in this way. Due to the redundant design (4-6 adsorbers parallel to the alternating adsorption and desorption) the product gas is produced without interruption.

Pressurised water scrubbing (PWS) is an absorptive biogas treatment process. In contrast to adsorption, absorption is the dissolving of gases in liquids (absorbent). Only water is used as an absorbent in pressurised water scrubbing. The process is based on the reversible absorption by physical binding forces (physisorption) of CO_2, but also of other acidic (e.g., H_2S) and basic (e.g., ammonia - NH_3) gas components in water. It is not necessary to pre-dry the raw biogas before gas scrubbing. A further side effect of this process is the fine desulphurisation of the biogas in the absorption column. Sometimes, depending on the H_2S content of the biogas, fine desulphurisation is nevertheless carried out upstream to protect the plant components from corrosion and also to prevent hydrogen sulphide from escaping in the exhaust air stream.

Depending on the manufacturer and requirements, the pre-treated biogas is compressed to 5 to 10 bar before entering the absorber. Since the compressed gas is heated during compression, it must then be cooled. The waste heat produced in this process can be decoupled and used, for example, for heating the fermenter. The absorber is usually designed as a trickle bed reactor, whereby the process takes place at a water temperature of approx. 15 to 20 °C. Low temperatures and increased pressure favour the absorption of CO_2 in the water. The escaping product gas biomethane is saturated with steam and is dried in an adsorption drying process. The water loaded with CO_2 is then regenerated in a two-stage process. In the first stage a partial flash column is used. In this phase, most of the methane dissolved in the water desorbs, but also some CO_2. To reduce the methane slip, the dissolving gas is fed back into the process. Subsequently, in the second stage, expansion to ambient pressure with simultaneous stripping by means of air takes place. The exhaust air (lean gas) produced in this process also contains CH_4 in small quantities, so that subsequent lean gas treatment is necessary. During stripping with air, a small amount of oxygen is dissolved in the process water, which can be converted into the product gas when reused in the absorption column. According to the manufacturer, however, a maximum concentration of 0.1% oxygen is not exceeded (Billig 2016).

The polyglycol wash (Genosorb®) is similar to the pressurised water wash (PWS). However, the solvent used for absorption is not water but an organic solvent. This is often referred to under the trade name Genosorb®. The process exploits the different solubility of the acidic components compared to the hydrocarbons. A major advantage over the PWS is the significantly higher solubility of CO_2. Therefore, considerably less washing liquid is required to desorb the same amount of CO_2 and the energy required for liquid circulation is lower. However, the desorption of the solvent requires not only pressure relief but also heating. A pre-drying of the raw biogas is achieved by condensation drying, in which the gas is compressed to approx. 8 bar before entering the absorption column and subsequently cooled and the condensed water is separated. A further side effect of this process is the possibility of fine desulphurisation of the biogas in the absorption column. However, since the regeneration of the loaded solvent from the H_2S is complex, fine desulphurisation is usually carried out upstream. Similar to PWS, CO_2 absorption takes place in an absorption stage at elevated pressure (approx. 8 bar) and desorption in a second stage in a flash column and a regeneration stage. The heat required in the regeneration stage can usually be covered internally from the lean gas aftertreatment. No external heat supply is required. The lean gas emitted in the regeneration stage is usually fed to a lean gas aftertreatment in the form of regenerative thermal oxidation (RTO) with an activated carbon unit connected upstream (for solvent cleaning), similar to pressurised water scrubbing.

The membrane separation process is based on the principle of separating methane and the other gas components by the different diffusion speeds of the different sized gas molecules through the membrane. The separation of carbon dioxide and methane is the more effective, the larger the membrane surface, the smaller the membrane thickness, the higher the partial pressure difference and the higher the selectivity of the membrane for the different gas components. At present, polymer-based hollow fibre membranes are used for the treatment of biogas. The process is relatively new in biogas upgrading and is currently in the market introduction phase. This means that relatively little practical experience is available, e.g., with regard to the service life of the membranes. The purity of the product gas increases as the membrane area increases. To improve the separation performance and to keep the methane content in the lean gas flow as low as possible, module circuits with recirculation can be used. To increase the methane content of the product gas, different module circuits are used. Two- and three-stage cascades have proven to be very promising. Although single-stage systems could also provide a satisfactory separation result, a comparatively low methane yield of around 80% and a correspondingly high methane slip must be expected. Since the waste gas stream still has a comparatively high methane concentration, it must be subjected to downstream lean gas aftertreatment. This is usually done by lean gas combustion or regenerative thermal oxidation.

Chemical absorption or amine scrubbing is characterised by the fact that physical absorption, the dissolution of the gas in the liquid, is followed by a chemical reaction between the dissolved gas component and the scrubbing liquid within the liquid phase. As a result, the binding of the undesired gas components to the scrubbing liquid is significantly stronger and thus the loading capacity of the liquid is many times higher than with purely physical absorption. The chemical reaction takes place very selectively, whereby the absorption of methane into the liquid can be reduced to a minimum. This allows a very high methane yield and a very low methane slip to be achieved. Due to the high affinity of carbon dioxide to the solvents used (mainly aqueous solutions of monoethanolamine MEA, diethanolamine DEA and methyldiethanolamine MDEA), the operating pressure of these plants can be chosen significantly lower than in comparable plants with pressurised water scrubbing. Typically, plants with amine scrubbing are operated without further compression at the pressure of the existing raw biogas. The high capacity and high selectivity of the amine solutions, a major advantage of the absorption process, results in a disadvantage when regenerating the scrubbing liquid. Chemically acting scrubbing liquids require the supply of a not inconsiderable amount of process heat (steam) during regeneration. The loaded amine solution is heated up to about 140-160 °C, whereby most of the bound carbon dioxide is released again and is produced as an almost pure gas stream at the outlet of the regeneration column. A small part of the scrubbing liquid is lost by evaporation into the biomethane stream and has to be replenished from time to time. This process could also be used to separate hydrogen sulphide from the raw biogas, but in this case regeneration would require the application of even higher temperatures. For this reason, the majority of commercial plants have realised that hydrogen sulphide is separated by fine desulphurisation before amine scrubbing. Waste gas treatment is not necessary in chemical scrubbing, as the process leads to high methane contents in the product gas and consequently to low methane emissions.

The following table summarises the five procedures with their main advantages and disadvantages.

	DWA	**PWS**	**Genosorb**	**membrane**	**Amine scrubbing**
Advantages*	No heat requirement	No heat requirement, easy to handle as no chemicals are used	Low power consumption, less effort for regeneration than amine scrubbing	Simple construction and operation, hardly any maintenance, small volume flows possible	low power consumption, very good loading capacity / selectivity
Disadvantages*	Relatively high power requirement, disposal of the adsorbent	High pressure required and therefore high power consumption	High heat demand	High power consumption, service life of the membranes still unclear	High heat demand, high regeneration effort
Methane slip *,** (Vol%)	1.5 – 2.3	1 -2.5	1	0.3 – 2.5	0.1

* (Dunkelberg 2015), ** (Billig 2016)

Technical development trends and development goals

Development goals at DWA, PWS and Genosorb are to further reduce the relatively high methane slip and electricity consumption. At present, only larger plants are economically viable (>500 Nm³/h biomethane). The development goal is therefore also to reduce the treatment costs for smaller plant capacities for decentralised biogas treatment. However, the process of upgrading to biomethane only contributes a small proportion of the total production costs. The majority of the costs of biomethane are incurred in raw biogas production, which has a comparatively low cost reduction potential (Billig 2016).

In the case of amine scrubbing, the focus of development is on heat recovery options. The use of amino acid salts as an alternative to amines is also a research objective. The advantage would be lower process temperatures for the regeneration of the washing solution, thus enabling the process for efficient biogas upgrading to be used in smaller biogas plants.

The development goal of the membrane process is to reduce the polymer-specific volume resistance by using new materials and to achieve technically interesting flow rates and thin and at the same time stable membranes.

The technological parameters were left unchanged for 2030 and set for 2050 on the basis of the following assumptions: The methane yield increases by 10% due to new bacteria, the auxiliary energy input for electricity and heat decreases by 10% due to more efficient technologies.

Current importance and outlook for 2030/2050

In Germany, only a small part of the approx. 8700 biogas plants (BGP) is operated with upgrading. In total, only about 150 biogas upgrading plants are in operation (Liebetrau 2017), in all of Europe about 250 with the main countries Germany, Sweden and the Netherlands. Great Britain, France and Italy are seen as countries with high potential, especially for the use of residual materials (Weber 2015). In Germany, pressurised water scrubbing, pressure swing adsorption and amine scrubbing are the dominant treatment processes in the plant stock (Dunkelberg 2015).

Biomethane as a renewable energy source is considered to have a significant potential as an energy carrier that can be stored in the gas grid and thus used in a wide range of applications, as it allows flexible use in the electricity, heat and mobility sectors. In the future, a coupling of biogas upgrading with power-to-gas (PtG) could become interesting. The technology would make it possible to methanise the CO_2 from the flue gas of biogas upgrading and feed it into the gas grid (Sterner 2010).

Technological parameters

Two reference installations are described: Reference plant biogas upgrading without heat demand (basis: DWA, PWS) and reference plant biogas upgrading with heat demand (basis: amine scrubbing). The reference processes for biogas upgrading were dimensioned according to the processes of the biogas plants with an upgrading capacity of 1,400 Nm^3/h biogas.

Reference plant Biogas upgrading without heat demand (basis: DWA, PWS, membrane)

A complete list of technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Operating hours	h/a	8,400	8,400	8,400
Biogas treatment capacity	Nm^3/h	1,400	1,400	1,400
Methane Volume flow CH_4 from biogas/agric. raw and residual materials	Nm^3/h	770	770	808
Methane volume flow CH_4 from biogas/biowaste	Nm^3/h	840	840	924
Methane content	%	97	97	97
Methane slip	%	0.1	0.1	0.1
Electricity demand per Nm^3 methane No heat requirement	MJ/Nm	2.3	2.3	2.2

Reference plant Biogas upgrading with heat demand (basis: amine scrubbing)

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Operating hours	h/a	8,400	8,400	8,400
Biogas treatment capacity	Nm^3/h	1,400	1,400	1,400

Methane Volume flow CH_4 from biogas/agric. raw and residual materials	Nm^3/h	770	770	808
Methane volume flow CH_4 from biogas/biowaste	Nm^3/h	840	840	924
Methane content	%	97	97	97
Methane slip	%	0.1	0.1	0.1
Electricity demand per Nm^3 methane	MJ/Nm	0.65	0.65	0.58
Heat demand per Nm^3 methane	MJ/Nm	6.12	6.12	5.51

Components

The reference plant biogas upgrading without heat demand consists of

- Coarse and fine desulphurisation (depending on H_2S content)
- compressor, drying by gas cooling
- Preparation unit
- Lean gas treatment (gas burner or regenerative thermal oxidation)
- The reference plant biogas upgrading with heat demand consists of
- Coarse and fine desulphurisation (depending on H_2S content)
- Amine scrubber
- Compressor, gas drying

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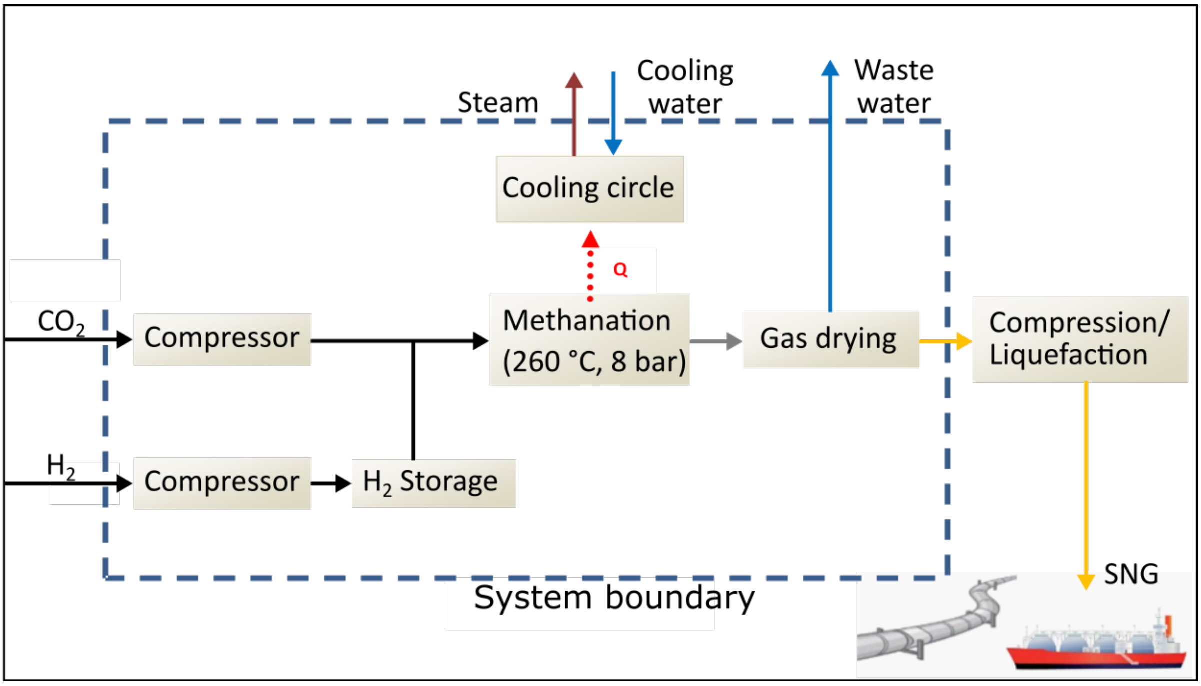
Module 18: Methanisation (H_2+CO_2)

Technology description

Figure 15: Overview of methane production



Source: own figure, ifeu

Methane synthesis is a catalytically assisted reaction that converts carbon dioxide and hydrogen into methane and water at 200 - 500 °C and 3 - 80 bar. This Sabatier reaction is known in the opposite direction as steam reforming of natural gas and is the most common process for producing hydrogen. (Sterner 2014)

The overall reaction of methanisation is strongly exothermic. Heat management that reliably dissipates the released energy is therefore essential to keep the methanisation reaction in a favourable temperature range and to shift the reaction equilibrium towards methane. This is why catalysts are used. Nickel is the first choice for this process due to its good availability, selectivity and activity in the reaction and its relatively favourable price. However, impurities or use in the wrong temperature range lead to deactivation of the catalyst, which is why high demands are placed on gas treatment and process control in chemical methanisation. (Grond 2013)

The most established - and so far the only commercially used - reactor concept is the fixed-bed reactor in the design as a tube bundle reactor. To ensure a uniform temperature control of the reactor, molten salt, thermal oil or steam are used for heat dissipation. For a feed-in of high quality into the gas grid (e.g., H-gas, >95% CH_4), the methane content of the product gas can be increased e.g., by a membrane process or a serial connection of reactors. The chemical efficiency at 100% conversion is 83% in relation to the calorific value. The remaining energy is released as reaction heat.

As a rule, the CO_2 must be brought to synthesis pressure by means of a compressor. An H_2 buffer can buffer a fluctuating supply of electricity. Water must be removed from the product gas coming out of the reactor in a gas dryer. The use of the process waste heat generated at a high temperature level (e.g., for CO_2-capture, electrolysis) can significantly improve the efficiency, economy and CO_2 balance of methanisation. (Sterner 2014).

In addition to the quantities of steel used in the construction of the plant, the catalyst materials used are of particular relevance to the life cycle assessment. The only direct emissions or waste are the effluents from the gas drying process and, if necessary, the cooling circuit.

Technical development trends and development goals

While methanisation of CO (synthesis gas) was already being used industrially for the production of artificial natural gas (SNG) from coal from the 1970s onwards, the first laboratory plants for CO_2 methanisation did not exist until the 1990s. Development was accelerated in the mid-2000s and the first industrial-scale plant was commissioned in 2013. The plant operated by Audi AG in Werlte, Lower Saxony, has a maximum electrical power consumption of 6.3 $MW_{electr.}$ and can produce up to 350 Nm^3 methane per hour. The exchange gas is fed into the local gas distribution network (L-gas, 1.8 bar). When the capacity of the distribution network is exhausted (summer case with low gas consumption) it is fed into the transport network (35-45 bar). (Zuberbühler 2011)

One aim of further development is on the one hand to optimise the existing industrial process - improved heat conduction, fast start-up and shut-down of the synthesis, simplified plant components and process control. In this context, the use of alternative catalyst materials and simplified reactor concepts (plate reactor) are also being investigated. Some new reactor concepts are either in the testing phase (honeycomb reactor) or in the laboratory phase (three-phase reactors, e.g., bubble column reactors with suspended solids). The development objective is usually better thermal management to extend the service life of the catalyst, improve the reaction kinetics and optimise the extraction of the reaction heat. (Sterner 2014)

Since the conversion of the educt gases in the reactor is already very efficient today, the greatest development potential lies in the use of the reaction heat for the extended power-to-methane process, i.e., the use for the separation of CO_2 and/or in (high-temperature) electrolysis.

While the Werlte plant will methanise pure CO_2 and H_2, some other demonstration projects are pursuing the direct ice feed of purified biogas (CH_4/H_2). In this case, additional steam usually has to be fed into the reactor to avoid deactivation of the catalyst (Sterner 2014). However, hardly any data are available on this technology.

Current importance and outlook for 2030/2050

Synthetically produced natural gas (SNG) is a fully fledged alternative to conventional natural gas. At present, the power-to-methane process does not represent economic competition to fossil fuels, as the production costs are significantly higher than the conventional gas price. The main cost factor is the electricity price for electrolysis.

Since SNG can be transported in compressed or liquefied form, there are hardly any restrictions on possible locations. In principle, the technology is also "island-compatible". Plants can be constructed in various size classes. Even today, start-up and shut-down times for a plant are in the range of a few minutes.

The opportunities of power-to-gas clearly lie in the use of the existing gas infrastructure, including end-user equipment such as gas-fired heating systems, gas cars and gas-fired power plants. Gas mobility is one of the first markets to emerge for power-to-gas. The bridge to the chemical industry can also be built, as methane is an important raw material for the industry.

Technological parameters

For the following technological and economic parameters, the plants at ZSW Stuttgart and Werlte were used (Specht 2016). A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
$\eta_{\text{chemicaly, LHV}}$	%	83	83	83
Heat T > 200°C	MJ	11	11	11
Heat T < 200°C	MJ	7.5	7.5	7.5
Pressure	bar	8	8	8
Temperature	°C	260	260	260

Components

Methanisation plants consist of

- Compressors
- H_2 buffer storage if necessary
- Reactor
- Heat exchanger
- Membrane separation
- Gas drying

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2.2 Modules on upstream chains and infrastructure

The modules on upstream chains and infrastructure are partly based on existing LCA data sets, e.g., from the ecoinvent database[1], which, however, had to be adapted for use in the present project. The technical parameters that serve as the data basis for this adaptation are presented in the following profiles.

2.2.1 Electricity generation on the basis of renewable energy

The production of synthetic energy carriers is based to a large extent on energy input through electricity. The technologies selected for this are described in the following profiles and serve to adapt existing LCA data sets within the project. However, for these technologies the location is an important factor to be considered in the LCA and cost analyses. In the following profiles, Germany is assumed to be the first location, unless otherwise noted. The location factors were examined in detail in the further course of the project in order to be able to adjust the parameters (e.g., full-load hours) and cost calculations for different production sites. The details are given in Chapter 4.4

Although the technical parameters differ only slightly, electricity generation by photovoltaics has been split into different modules to take account of the much greater differences in costs. Further modules that reflect the mix of photovoltaics at the relevant locations can be assembled from these modules and the location factors shown in Chapter 4

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[1] Wernet, G., C. Bauer, Steubing, J. Reinhard, E. Moreno-Ruiz, (2016). "The ecoinvent database version 3 (part I): overview and methodology." The International Journal of Life Cycle Assessment 21(9): 1218-1230.

Wind turbines
Module 19: Wind onshore
Module 20: Wind offshore

Technology description

Wind turbines convert the kinetic energy of the wind into rotational energy and then into electrical energy via generators (Wietschel 2015). The plants are currently mainly built in a range of 1 - 6 MW per plant, often in the context of wind farms. The classification is made according to:

- Location: onshore and offshore,
- Technology of mechanical power transmission: gearless and with transmission,
- Wind strength: strong wind and weak wind turbines

Offshore wind turbines achieve around 40% higher yields per installed unit of capacity compared to onshore turbines due to the higher and more uniform wind speeds, but with higher costs for the foundation of the turbines and grid connection (Pregger 2012).

Technical development trends and development goals

The technology of wind turbines is fully developed in terms of fluid mechanics. In the future, wind turbines will be further differentiated by different generator concepts, rotor diameters and innovative tower construction concepts. Currently, larger hub heights and rotor diameters are being aimed at in order to achieve higher performance and a more uniform yield.

Permanent magnets are increasingly used in new plants. These use rare earths such as neodymium and dysprosium (IWES 2015), whose availability must be critically reviewed in the long term.

Current importance and outlook for 2030/2050

In 2016, 48 GW of onshore wind turbines were installed worldwide and around 3 GW of offshore wind turbines. The stock thus rose to 453 GW onshore and 14 GW at sea (IRENA 2017). However, a strong increase in offshore wind is expected, as many offshore wind farms are already under construction or in the process of being approved. The trend towards gearless wind turbines is still concentrated on onshore plants, where they accounted for between 40 and 50% of installed capacity in Germany in recent years (IWES 2015).

Technological parameters

Modules were created for the following wind turbines, the technical parameters were estimated according to (Steurer 2018) and compared with (Nitsch 2012, IEA 2016) In each case, these are average turbines as they are built in the respective reference year. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Wind onshore (strong wind)

Technical parameters plant	**Unit**	**2015**	**2030**	**2050**
Typical output	MW out	2.9	3.8	6
Full load hours	h/a	3200	3650	4100
Lifetime	a	20	25	25
Hub height	m	100	115	140
Rotor diameter	m	101	124	168

Wind offshore

Technical parameters plant	Unit	2015	2030	2050
Typical output	MW out	4.15	8.5	15
Full load hours	h/a	3888	3952	4000
Lifetime	a	20	25	25
Hub height	m	90	112.5	165
Rotor diameter	m	120	172	235

Components

The results of the UBA project "Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen" [UBA 2019] were used for the production and operation of wind power and PV plants.

Wind turbines consist of the following components:

- Foundation
- Rotors
- Generators
- Gondola
- Tower
- Cabling, switching and control systems

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Module 21: Run-of-river power Central Europe/Scandinavia

Technology description

Due to its long tradition, hydropower is already largely developed in Europe. The range of hydropower in general extends from very small plants in the kW range to very large dams. The Itaipu Dam in Brazil with 14 GW and the Three Gorges Dam in China with 22 GW are currently the largest plants worldwide (IRENA 2012). Hydropower plants are designed for a very long service life (up to 100 a with retrofit), but only in combination with a large water storage facility do they offer the possibility of generating electricity in line with demand. The plants are categorised accordingly according to their storage capacity:

- Run-of-river power plants: Electricity production depending on the watercourse in the river; low or short-term storage capacity, relatively low costs,
- Storage power plants: large reservoirs, often with high head; seasonal storage, generation according to demand,
- Pumped storage power stations: Allow water to be pumped back during periods of excess electricity.

In addition, hydroelectric power plants are classified into small, medium and large. In the EU language, plants <20 MW are considered "small", while Norway already draws the line at 10 MW.

Technical development trends and development goals

Hydropower plants are technically very advanced. In future, innovations are to be expected less in power plant technology than in the management of the catchment area. Key development goals relate to improved resource management and the avoidance of environmental effects (water quality, biodiversity/fish, erosion & bed load, etc.) (Keuneke 2015). These will increasingly lead to accompanying measures, thus limiting cost reduction potential.

Current importance and outlook for 2030/2050

Globally, hydropower is currently still the most important renewable energy source for electricity generation. However, a large part of its potential has already been exploited. In Germany, a low expansion potential of 2.7 to 4 TWh per year has been identified for large water bodies (Anderer 2010, Keuneke 2015). As a result of climate change, energy generation from hydropower could decline by 5 to 15% in the future, at least in Germany (Anderer 2010).

Hydropower is currently still the only technology that can provide storage on a large scale at low cost. Due to their quick-start and partial-load capability, hydropower plants are important components for stabilising the interconnected grid, especially with increasing feed-in of wind and solar power (IRENA 2012). Due to the lengthy planning phase of hydropower projects, expansion is expected to be slow but constant (IRENA 2012). (Pumped) storage power plants are therefore unlikely to be considered for the generation of synthetic energy carriers.

Technological parameters

The supply of electricity from hydropower is concentrated here on run-of-river power plants, which achieve high annual full-load hours with low storage capacity and relatively low installed capacity. The focus here is on plants of up to 10 MW, which could still be built in Central Europe and Scandinavia. No further modules for mapping different hydropower mixes with storage option were used. The generation of synthetic energy carriers would lead to increased competition for electricity storage and thus to cost increases. The technical parameters have been defined on the basis of (Others 2010, IRENA 2012, Nitsch 2012) until 2050. A complete list of the technology parameters can be found on the website of the Federal Environment Agency. Since hydropower is technically largely mature, no changes in the technical parameters are assumed, but only that efficiency is maintained through retrofitting measures (Anderer 2010).

Run-of-river power

Technical parameters plant	**Unit**	**2015**	**2030**	**2050**
Typical output	MW out	10	10	10
Full load hours	h/a	5000	5000	5000
Electrical efficiency	%	95	95	95
Lifetime	a	40	40	40

Components

For hydropower plants, the following components are considered according to the available life cycle assessment data according to (Wernet 2016):

- Dam with inlet and outlet
- Turbine
- Generator
- Transformer

References

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Photovoltaics
Module 22: PV roof monocrystalline
Module 23: PV ground-mounted polycrystalline

Technology description

Photovoltaic (PV) technologies generate direct current from solar radiation energy. A detailed description of the relevant technologies can be found in (Wietschel 2010), where a distinction is made between the following cell concepts, which are currently widely available on the market

- c-Si (monocrystalline silicon): Solar cells based on monocrystalline silicon doped with phosphorus and boron,
- poly-Si (polycrystalline silicon): single-layer solar cells based on polycrystalline silicon, also doped with phosphorus or boron,
- Thin-film technologies: single-layer, thin amorphous semiconductor layer on substrate material based on the following compounds: CdTe (cadmium telluride); CI(G)S (copper indium (gallium) selenide or sulphur); amorphous silicon (a-Si).

The electricity production of a PV system depends on the one hand on the location and the available radiation and on the other hand on the efficiency of the systems. In Germany, an average of around 980 full load hours (FLH) was achieved between 2012 and 2016 for ground-mounted systems and 890 FLH for roof-mounted systems (Wirth 2017).

In 2015, the efficiency of crystalline modules was 12-20%, although it has risen constantly by about 0.3% per year in recent years (Wietschel 2015). Although much higher efficiencies of cells have been proven in the laboratory, these cannot yet be achieved in series production and, due to design constraints, in practical operation. Module efficiency is increasing along the following sequence: thin-film < mc-/poly-Si < c-Si; in the same sequence, costs, material and energy requirements during production are increasing, which has led to a market niche for thin-film modules especially in open-space plants. However, c-Si and mc/poly-Si modules have become significantly cheaper in recent years (NREL 2015, Rech 2016), which is why the importance of thin-film modules tends to decline (see also next chapter).

C- and poly-Si do not contain any materials classified as quantity critical or toxic, unlike, for example, thin-film technologies based on CdTe.

Technical development trends and development goals

Future developments in poly- and monocrystalline PV systems are described (Wietschel 2010, NREL 2015, Wietschel 2015, Rech 2016). The central goals of PV development are to increase efficiency and reduce material consumption.

By 2050, efficiency increases for PV systems in long-term practical use are expected to reach 18-20% and the target is 25%. This is to be achieved, among other things, by means of a higher packing density. In the future, material efficiency and energy use are also to be further improved and the service life increased through more effective production processes for manufacturing modules and substructures. In addition, the replacement of certain materials is being sought, e.g.:

- Replacement of silver by copper or aluminium,
- Replacement of lead e.g., in soldered joints with other materials.

In the field of PV, numerous alternative technologies are being researched which could lead to technological leaps in the future, e.g., concentrating PV in regions of high irradiation (not in Germany); tandem/triple-layer PV; organic PV; perovskite modules; new concepts for thin-film technologies. Due to the early stage of development and the resulting data situation, these technological leaps are not considered within the project.

Current importance and outlook for 2030/2050

The importance of PV has increased significantly worldwide in recent years (Fraunhofer ISE 2016, Fraunhofer ISE 2017). In 2015, 52 GWp of PV modules were produced worldwide, of which were

- monocrystalline: 24%,
- multicrystalline: 69%,
- thin film: 7%, strongly fluctuating, with CdTe (60%) dominating, ahead of CI(G)S (26%) and a-Si (14%)

In 2016, 77 GW were installed, the cumulative total capacity was 320 GW. In principle, all module types can be used in both ground-mounted and roof systems. Monocrystalline and multicrystalline cells currently dominate the market. The share of thin-film PV is declining and is becoming less and less economically competitive due to its lower efficiency. Thin-film (CdTe) may still be relevant for ground-mounted systems, where the space efficiency (yield per area) is less of a restriction than for roof systems. The price advantage of cheap but less efficient thin-film modules is diminishing as c-Si and mc-/poly-Si modules have become significantly cheaper in recent years (NREL 2015, Rech 2016). There is a lot of research on new technologies, but it is still unclear when and to what extent they will be used in which markets or niches. Globally, concentrating systems could also play a role in countries with high solar radiation. According to the current state of knowledge, systems based on c-Si, mc-/poly-Si and CdTe, possibly differentiated by location and size class, will continue to be used in Germany.

Technological parameters

For PV, a module based on monocrystalline silicon was defined for roof systems and a module with polycrystalline silicon for an ground-mounted system. For these modules, basic data records are available within the ecoinvent database (Wernet 2016). These were supplemented by data from the UBA project "Updating and assessment of life cycle assessments of wind energy and photovoltaic systems taking into account current technological developments" [UBA 2019].

The modules are initially shown with a full-load hour count for a good location in Germany. With regard to plant sizes and costs, these represent two different concepts. In the current project, these LCA data are updated on the basis of the following technology data, which are based on (Steurer 2018) and have been compared with (Nitsch 2012, Wietschel 2015, IEA 2016). A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Typical output roof monocrystalline	MW out	0.005	0.005	0.005
Typical performance ground-mounted polycrystalline	MW out	5	5	5
Full load hours	h/a	1050	1050	1050
Lifetime	a	20	25	30
Degradation	%/a	0.4	0.4	0.4

Further PV variants for EU countries or the Middle East and North Africa (MENA) can be generated from the two modules by linking them to other irradiation data. These modules then contain the same technology data, but different site conditions and cost data.

Components

Photovoltaic systems consist of the following components, which are considered in the available LCA data according to (Wernet 2016). These were supplemented by data from the UBA project "Aktualisierung und Bewertung der Ökobilanzen von Windenergie- und Photovoltaikanlagen unter Berücksichtigung aktueller Technologieentwicklungen" [UBA 2019]:

- Solar modules
- Inverter for conversion to alternating current
- Cabling
- Substructure

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Module 24: Electricity from geothermal energy Iceland

Technology description

Electricity generation from geothermal energy uses hydrothermal reservoirs. In particular, high-enthalpy deposits with temperatures >200 °C can be used efficiently to generate electricity directly via steam turbines. In Europe, high-enthalpy deposits are geographically very limited to Iceland, Italy and Turkey (Antics 2007). Geothermal energy is an interesting option for the supply of synthetic energy carriers due to its base-load capable electricity generation, as it ensures high capacity utilisation of production facilities. However, the risks of drilling and thus the costs of exploring and developing suitable deposits are difficult to estimate (Rogge 2004, Bundesverband Geothermie 2017).

Technical development trends and development goals

Efficiency improvements are the main objective of technology development, which is aimed in particular at generating electricity from low temperatures. Due to the rather small number of plants and the specific site conditions, it is not possible to update the data for 2050.

Current importance and outlook for 2030/2050

The use of geothermal energy for electricity generation is only increasing slowly. In 2015, around 13 GW were installed worldwide, of which about 12% in Europe. The highest installed capacities within Europe are found in Iceland with 0.9 GW and Italy with 0.7 GW (Bundesverband Geothermie 2017). Due to the natural conditions and the complexity of the plants, a massive expansion is not expected in the near future.

Technological parameters

Very little data is available for geothermal plants, especially as the sites in Europe are quite limited. For this reason, an individual plant was selected here as a reference plant for geothermal electricity generation for the preparation of the profile. Data from an existing CHP plant in Iceland are used according to (Karlsdóttir 2015), which is among the largest in the world with a capacity of 303 MW_{el} and 133 MW_{th}. Although this plant combines electricity generation with heat supply, each of the plants is a separate unit, which means that it can still be used for the LCA. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Geothermal energy Iceland

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Typical output electricity	MW out (el)	303	303	303
Typical output heat	MW out (th)	133	133	133
Full load hours	h/a	7620	7620	7620
Electrical efficiency	%	17	17	17
Temperature level (electricity)	°C	180	180	180
Lifetime	a	30	30	30

The design and cost of building geothermal plants are extremely site-specific. Therefore this module is only valid and available for the specific location Iceland. As there is little data available for such geothermal plants, these parameters have been kept constant until 2050.

Components

The geothermal CHP plant consists of the following components

- Well system with boreholes
- Power station
- Heating plant

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Concentrating Solar Power (CSP)

Module 25: CSP Medium Load (Solar Multiple 2.0, 8h storage)

Module 26: CSP Base Load (Solar Multiple 3.0, 14h storage)

Module 27: Parabolic trough (PT)

Module 28: Solar tower (ST)

Technology description

With Concentrating Solar Power (CSP), direct normal solar radiation (Direct Normal Irradiance or DNI) is concentrated by means of curved mirrors onto a focal point or focal line (receiver). Depending on the technology, the mirrors have different shapes and arrangements: In parabolic trough power plants, the sunlight is concentrated in a linear manner, whereas in solar towers, a heliostat field concentrates the sunlight to a spot at the top of a tower (DCSP 2017).

A heat transfer fluid (HTF) is heated in the receiver. Depending on the concentration factor and HTF used, temperatures between 390 °C and 550 °C can currently be reached (SolarPACES 2017). The solar heat thus obtained from the solar field can either be used directly to operate a steam turbine or temporarily stored in a thermal storage tank (Denholm 2011). The heat can be used to generate electricity, heat, cold, solar fuels or for water purification (Pregger 2009, Trieb 2007). CSP power plants for electricity production are currently in operation on several continents. Due to the fact that CSP does not use diffuse solar radiation, this technology is only suitable for locations with a high DNI (guideline value: DNI > 2,000 kWh/m²/a). The typical minimum capacity for CSP power plants for commercial electricity production is 50 MW. Larger power plants reach up to 250 MW (NREL 2017).

Technical development trends and development goals

For parabolic trough power plants it is assumed that after 2030 molten salt will replace the thermal oil used today as HTF for the solar field. The advantages would be the higher temperature and the associated higher thermodynamic efficiency in the steam turbine. Investment cost degression of up to 35% is also expected for a solar field. For concentrating solar power plants, an increase in the efficiency of both the heliostat field (55% in 2015, 59% in 2030) and the power block is expected due to the higher temperatures (up to 600 °C in the case of the solar tower).

The cost degression for the heliostat field should be around 30% between 2015 and 2030, if the globally installed capacity is to develop according to an average scenario (Giuliano 2016).

Current importance and outlook for 2030/2050

At the moment there are about 5 GW CSP installed and in operation worldwide. About 4 GW are under development or construction. The majority of CSP power plants use parabolic troughs (more than 80% of the plants in operation or under construction). Solar tower technology follows with a market share of about 15% (NREL 2017).

The development scenarios for the year 2030 are very heterogeneous, with installed capacity varying between 10 GW and 635 GW. On average, this results in around 210 GW, with very different assumed cost developments depending on the scenario. Regardless of the development of installed capacity, the learning rate for CSP is in the range of 10% - 12% (per doubled installed capacity). In contrast, the learning rate for PV & battery systems is 15% - 20% (Breyer 2016).

Technological parameters

In the current project, the following modules are considered, which represent two technologies for the solar field, including steam turbine and cooling, namely parabolic trough (PT) and solar tower (ST).

In addition, there is a subdivision into modules that map different storage capacities:

- CSP medium load (Solar Multiple 2.0, corresponds to 8 h storage)
- CSP base load (Solar Multiple 3.0, corresponds to 14 h storage)

These modules can be combined with each other within the supply paths. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Parabolic Trough Power Plant

General technical parameters PT	Unit	2015	2030	2050
Max. temp. HTF	°C	393	485	600
Turbine efficiency (gross)	%	37.2	40.2	43.4
Design efficiency plant (gross)*	%	28.1	28.9	29.8
Annual plant efficiency (net)*	%	17.2	18.1	19.3
Lifetime	a	25	25	25
Availability	%	96%	97%	98%

*The values apply to dry cooling. For wet or evaporative cooling higher efficiencies can be achieved depending on the location and local meteorological conditions (up to approx. 7-8% higher efficiency).

Solar Tower

General technical parameters ST	Unit	2015	2030	2050
Max. temp. HTF	°C	550	580	650
Turbine efficiency	%	42.1	42.9	44.5
Design efficiency plant (gross)	%	23.4	24.8	28.0
Annual plant efficiency (net)	%	12.2	13.3	15.9
Lifetime	a	25	25	25
Availability	%	96%	97%	98%

Solar Multiple 2.0 (corresponds to 8 hours of heat storage): Medium load

Technical parameters SM 2.0	Unit	2015	2030	2050
Full load hours PT	h/a	4080	4140	4230
Full load hours ST	h/a	4480	4545	4650

Solar Multiple 3.0, (corresponds to 14 hours of heat storage): Base load

Technical parameters SM 3.0	Unit	2015	2030	2050
Full load hours PT**	h/a	6420	6515	6670
Full load hours ST**	h/a	6890	6995	7160

**The values apply to a representative location in the MENA region.

Components

CSP plants consist of the following components:

- Solar field (parabolic trough collectors or heliostats)
- Separate receiver if necessary (only for tower power plants)
- Thermal storage (typically 2-tank indirect or direct storage with "Solar Salt" (molten salt)
- Power Block (heat exchanger, steam turbine, condenser)

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2.2.2 Sourcing of biomass

Essential information on biogenic residues and waste is based on the JRC report "Solid and gaseous bioenergy paths: input values and GHG emissions" (JRC 2014) and the UBA study „Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm)“ (BioEM 2016), which builds on the JRC report.

In this project, residual materials receive ecological burden only from the point of collection, in line with the RED (Renewable Energy Directive of the EU). However, if the collection of residual materials has an impact on another system, this must be taken into account. An example is the use of straw, which is also a removal of nutrients from the soil. A compensation for these withdrawals is also included in the calculation of the default values of RED II (Edwards 2017). [2]

The identification of biomass potentials in Germany and the EUMENA region and a selection of supply paths based on these is presented in Chapter 4.2. However, the technology profiles in this chapter already include assessments of potentials for residual and waste materials to illustrate their current importance and provide an outlook for 2030/2050. These potential assessments draw partly from the UBA study "Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem (BioRest)" (BioRest (2019)). BioRest distinguishes between two development scenarios that describe a basically accessible use corridor:

- The ‘Business as Usual (BAU)’ case - as a mixture of the currently existing and legally binding with voluntary restrictions - and a
- The case ‘MER - With extended restrictions’

For the modules of cultivated biomass, data (not potentials) on cultivation in the EUMENA region are also given. The basis for the calculation is essentially the BioGrace calculator (www.biograce.net), the projections of the Food and Agriculture Organisation (FAO) and, for Germany, the UBA study " Germany in 2050 – a greenhouse gas-neutral country "[3], or its successor "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE[4]".

Whether biomass should still be used to produce energy in the future is a political decision. In the UBA studies „ Germany in 2050 – a greenhouse gas-neutral country “ and its successors " Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality – RESCUE ", it is assumed that biomass will no longer be used for energy purposes in 2050. For the modules "sourcing of biomass" within the framework of this project, this is not relevant for the life cycle assessments. The data included in the analysis - environmental impacts of cultivation/collection, transport, and processing - are largely independent of whether and to what extent these supply paths will be used in the future.

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[2] Edwards, R., Padella, M., Giuntoli, J., Koeble, R., O'Connell, A., Bulgheroni, C., Marelli, L., Definition of input data to assess GHG default emissions from biofuels in EU legislation, Version 1c - July 2017, EUR 28349 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-64617-1, doi:10.2790/658143, JRC104483

[3] UBA (2014): Treibhausgasneutrales Deutschland 2050- background paper. Climate Change 07/2014, UBA, Dessau 2014

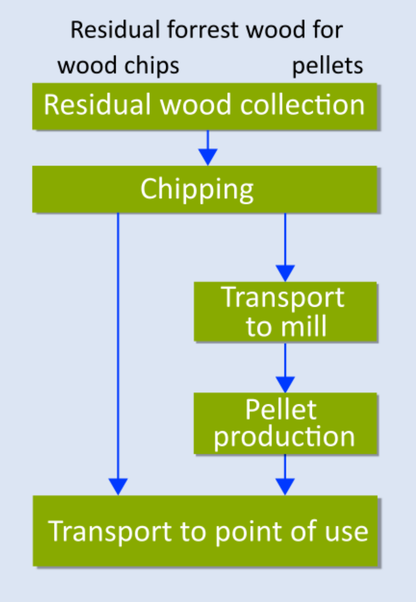
[4] UBA. (2019): Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality – RESCUE: Summary Report. Umweltbundesamt. https://www.umweltbundesamt.de/en/rescue/summary_report

Module 29: Forest residual wood

Technology description

Forest residue wood consists of branches, weak wood, trunk parts, stumps, etc., which accumulate during thinning and harvesting and is not suitable for industrial processing. It often remains in the forest and is no longer used.

Figure 16: Steps for processing residual forest wood into wood chips / pellets



Source: own figure, ifeu

In analogy to RED, no prior charges are credited beyond the point of collection. If this balance were to take into account the change in carbon stocks in the forest system, the impacts of the removal of residual forest wood would have to be included. Due to the scientific uncertainties in these calculations, this is not included here.

Forest residue wood can be used for the production of (P)BtX energy carriers both as wood chips and as wood pellets. Pellets have a lower moisture content and can therefore be transported more efficiently. In addition, some technical BtL concepts require the use of pellets, as their homogeneity makes them easier to process in some plants.

The supply of **wood chips** from residual forest wood includes the process stages of collection, storage, chipping and transport. For residual forest wood, no expenses for silviculture are assumed, but for the collection and bundling of the material. After collection, the unchipped wood is stored in the forest for several months and undergoes natural drying. In principle, the chipping can take place in different places. On the one hand, it is possible to chop on the back road, on the forest road or at a central collection point. The standard procedure in Germany is processing with mobile chippers on the forest road. Chipping at central locations, such as in energy wood logistics centres, is becoming increasingly important.

In (JRC 2014) and (BioEm 2016), 0.012 MJ diesel per MJ of wood is currently specified for collection and bundling. In the storage phase, the moisture content is reduced from 50 to around 30%. Microbial decomposition also reduces the dry matter by around 5%. Shredding is assumed to be 0.00336 MJ diesel per MJ wood chips (with a water content of 30%) for 2015.

The transport route of wood chips to the BtX plant also depends on their size, which determines the catchment area. The base case, BioEm (2016) assumes a transport distance of 500 kilometres (with a total weight of 40 t by truck). In this study, the transport distances can be varied according to supply path and location.

Wood pellets are standardised cylindrical pressed pellets, usually made of dried, natural residual wood, with a diameter of approximately 6 to 8 mm and a length of 5 to 45 mm. They are produced in so-called pelleting plants. (JRC 2014) assumes that fresh wood chips (with the corresponding energy consumption for collection, bundling and chopping (50% moisture) are used. The transport route to the mill is assumed to be 50 kilometres in the base case of this study. First of all, the wood to be processed must be dried with a belt or drum dryer to a final water content of 10%. Then the raw materials are crushed in a hammer mill. This is followed by pelleting in a pellet press and cooling of the produced wood pellets.

The table "Technological parameters" of this module shows the electricity and steam requirements for pellet production. The basic variant for this study is the supply of heat by natural gas boilers and of electricity from the general grid. In the calculations of (JRC 2014) and (BioEm 2016) further variants are distinguished:

- Electricity and heat from natural gas cogeneration
- Electricity from the grid, heat from woodchip cogeneration
- Electricity and heat from woodchip CHP

The transport route of wood pellets to the BtX plant also depends on their size. For the base case, a transport distance of 500 km with a truck total weight of 40 t is assumed in accordance with (BioEm 2016). In this study, the transport distances can be varied according to supply path and location.

Technical development trends and development goals

It can be assumed that the above-mentioned energy requirements and the choice of process energy will change by 2050. Progress in efficiency is possible, but above all the use of alternative energy carriers. The use of wood fuels instead of natural gas for drying is already widely implemented today, and by 2030 it can be assumed that only biomass will be used as an energy source (also for electricity from CHP). With regard to efficiency, only little potential can be assumed, as the technologies involved are very robust (mechanical processing, drying).

Current importance and outlook for 2030/2050

Today, the available potential of residual forest wood is usually estimated for forest enterprises using various methods. The general amount of wood available can be estimated with the help of data from the Federal Forest Inventory. It is very difficult to derive forest wood potentials for energy use, since the market dictates which potentials go into energy and which into material use. However, it is basically possible to define that the range of trunk wood is not used for energy purposes. Depending on the market situation, usage shifts between energy wood and industrial wood.

Based on the study "Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem (Elektrizität, Wärme und Transportsektor)" (BioRest (2019)), the future potentials of two models are used in the sense of mapping a use corridor that can be developed in principle. The "BAU" and "With Extended Restrictions" models are described at the beginning of Chapter 2.2.2

The BAU model assumes a potential of around 10 million $t_{\text{abs. dry}}$/year in 2050. In the model "With extended restrictions" it is assumed that the coniferous energy wood potentials in 2050 will be used entirely for material purposes. This reduces the energy wood potential to around 6 million $t_{\text{abs. dry}}$, which corresponds to the share of hardwoods.

In the UBA studies “Germany in 2050 – a greenhouse gas-neutral country“ and its successor "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE", it is assumed that biomass will no longer be used for energy in 2050. Nevertheless, the ecological impacts are quantified in this study.

Technological parameters

The following technological parameters represent the basic cases from (BioEm 2016) to produce wood chips and pellets from residual forest wood. Variants for energy supply can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Energy consumption Collecting and bundling	MJ /MJ Wood	0.012	0.012	0.012
Energy consumption shredding	MJ /MJ wood chips	0.00336	0.00336	0.00336
Water content wood chips for end use	%	30	30	30
Water content wood chips for Pelletising	%	50	50	50
Calorific value (LHV) wood chips (humidity 30%)	MJ/kg	12.3	12.3	12.3
Bulk density wood chips (moisture 30%)	kg/m^3	220	220	220
Bulk density wood chips (moisture 50%)	kg/m^3	310	310	310
Transportation of wood chips to the pelletising plant	Km	50	50	50
Transport distance wood chips to the BtX plant	Km	500	500	500
Electrical energy pelletising plant	kWh/t$_{\text{pellets}}$	237	237	237
Pellet factory heat requirement	MJ/t$_{\text{pellets}}$	3200	3200	3200
Water content pellets	%	10	10	10
Calorific value (LHV) Pellets	MJ/kg	17.3	17.3	17.3
Bulk density pellets	kg/m^3	720	720	720

Sustainably usable potentials in Germany according to BioRest (2019)

Technical parameters	**Unit**	**2015**	**2030**	**2050**	**Comment**
Potential Germany Model "Business as Usual"	Mio t$_{\text{abs. dry}}$	10	10	10	BioRest (2019)
Potential Germany Model "With extended restrictions“	Mio t$_{\text{abs. dry}}$	10	10	6	BioRest (2019)

Components

The supply of residual forest wood as BtX raw material includes

- Collection and bundling
- Drying in air
- Chopping
- Transport
- Pelletising if necessary

References

BioRest (2019). BioRest: Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem, Umweltbundesamt, Texte 115/2019

BioEm: Fehrenbach, H., Köppen, S., Markwardt, S., Vogt, R. (2016): Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm), UBA Texte 08/2016. Umweltbundesamt, Projektnummer 28232. Dessau-Roßlau. 2016

JRC - Joint Research Centre (2014): Solid and gaseous bioenergy pathways: input values and GHG emissions; Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259; JRC Report EUR 26696 EN; Ispra 2014.

Module 30: Liquid manure (slurry)

Technology description

Liquid manure or slurry is a mixture of excrement and urine from cattle, pigs or other farm animals, which may also contain water (cleaning water, rainwater), feed residues and litter. The water content is assumed in this study to be 90%, as in JRC 2014 and BioEm 2016.

In terms of the ecological balance sheet, liquid manure is waste that does not carry any ecological burden until it is transported away. As in (JRC 2014) and (BioEm 2016), the transport route to the biogas plant is assumed to be 5 km (one way by truck total weight 40 t).

Technical development trends and development goals

With regard to collection and transport, no relevant changes in the future scenarios can be assumed compared to the above-mentioned approaches.

Current importance and outlook for 2030/2050

Animal excrements, especially liquid manure, have been increasingly used for biogas production since the advent of biogas plants. Nevertheless, direct use as farmyard manure still dominates, so that a high proportion of the material flow is not yet used for energy production.

The basis of all potential analyses for liquid manure are the current numbers of animals. Consumer behaviour is decisive for the future development of animal numbers and thus the future potential of liquid manure. The share of organic livestock farming also plays a role. On the one hand, the amount of liquid manure that can be used for energy purposes is lower in pasture farming than in livestock housing. On the other hand, the animals in organic farming produce less liquid manure due to the composition of their feed.

In the study " Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem (Elektrizität, Wärme und Transportsektor)" (BioRest (2019)), two models are used for the future potential in the sense of mapping a utilisation corridor that can be developed in principle. The "BAU" and "With Extended Restrictions" models are described at the beginning of Chapter 2.2.2

The currently estimated residual material potential of liquid manure is stated in (BioRest 2019) at 96 million t_{FM}. In weighing up opposing influences (high building requirements, strongly fluctuating milk prices, changes in diet in relation to the increased population and birth rate), the currently assumed values are continued as constant in the "BAU" model.

In the model "With extended restrictions" it is assumed that the share of organic farming will rise to 20%, as targeted by the Federal Government. Lower animal output in organic farming means that animals excrete less excrements. Developments in livestock numbers are also fundamentally important. (BioRest 2019) therefore assumes a decline to 74 million t_{FM} by 2050.

Technological parameters

The following technological parameters are based on (JRC 2014) and (BioEm 2016). A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Water content liquid manure	%	90	90	90
Transportation of liquid manure to the biogas plant	Km	5	5	5

Useable potential in Germany according to BioRest (2019)

Technical parameters	**Unit**	**2015**	**2030**	**2050**	**Comment**
Potential Germany Model "Business as Usual"	million t_{FM}	96	96	96	BioRest (2019)
Potential Germany Model "With extended restrictions“	million t_{FM}	85	74	74	BioRest (2019)

Components

The supply of liquid manure as BtX raw material includes only the transport

References

BioRest (2019). BioRest: Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem, Umweltbundesamt, Texte 115/2019

BioEm: Fehrenbach, H., Köppen, S., Markwardt, S., Vogt, R. (2016): Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm), UBA Texte 08/2016. Umweltbundesamt, Projektnummer 28232. Dessau-Roßlau. 2016

JRC - Joint Research Centre (2014): Solid and gaseous bioenergy pathways: input values and GHG emissions; Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259; JRC Report EUR 26696 EN; Ispra 2014.

Module 31: Straw

Technology description

Straw is referred to in the agricultural context as a by-product and is defined as dry stalk, stem and leaf of threshed cereals, pulses, oil and fibre plants. With an average of 30 million t_{FM}/a (tonnes of fresh matter per year), cereal straw has the largest share in Germany, followed by rape straw with 7.5 million t_{FM}/a and maize straw with 4 million t_{FM}/a. Straw is already used to a considerable extent for material or energy purposes. For example, about five million tonnes of straw are used as bedding material in livestock housing. Rapeseed and grain maize straw usually remains on the field for humus reproduction. In comparison, the use of agricultural residues as solid fuel is currently marginal: It is currently estimated that 25 to 50 (small) combustion plants in Germany are operated on the basis of straw and that less than 10,000 tonnes are used for this application (Zeller 2014).

In general, and in analogy to RED, residual materials are only credited to the eco-balance from the point of collection. In the case of straw, however, the removal of straw is also associated with the removal of nutrients, which must be returned to the system. In analogy to (Edwards 2017), this is done by means of a supplement through compensatory fertilisation. It is assumed that the amount of straw withdrawal does not lead to a deterioration of the humus balance. Straw can be used both as chopped straw and as straw pellets. Certain technical BtX concepts require the use of pellets, as their homogeneity makes them easier to process in some plants.

Common to both forms of processing is the recovery of straw from the field as bales of straw. Depending on the type of fruit, weather and region, the grain is harvested in the period from June to September. The farmer aims to harvest his grain with a high dry matter content (from ≥ 86%). After threshing, the straw is collected in rows by the combine harvester or a windrower (placed on a swath). Essential for salvage is the height of the grain or straw yield, the stubble height and the proportion of short straw that cannot be salvaged. Using an agricultural tractor with a towed baler, the stalks are processed into bales of straw, which are compressed and fixed. Depending on the type of baler, round or square bales of different sizes and bale densities can be produced. The bales are usually stored temporarily in the field and then transported to the biogas, pelletising or BtX plant. In (JRC 2014), 0.010 MJ of diesel per MJ of straw are specified for the recovery of straw in 2015.

In the pelletising plant, the straw bales are transferred into a continuous material flow by means of bale breakers. The straw is then first roughly chopped and then finely shredded with the aid of granulators. For optimum adjustment, the straw is pretreated in a mixer by adding water to a water content of about 14%. The pre-treated material then passes into the pellet mills. After pelleting, the pellets produced can have temperatures of 80 - 130 °C. The subsequent cooling, mostly according to the counter current principle, further increases the dimensional stability and storage stability of the straw pellets. In (JRC 2014), 0.020 MJ of electrical energy per MJ of straw pellets are specified for Pelletising of straw for 2015.

The transport route to the processing plants also depends on their size, which determines the respective catchment area. For the base case, this study assumes (Zeller 2015) a transport distance of 10 kilometres to a biogas plant, 50 kilometres to a pelletising plant and 100 kilometres to a BtX plant. In this study, the transport distances can be further varied according to supply path and location. In JRC (2014), the transport of straw (total weight 40 t by truck) is estimated at 0.0070 MJ diesel per MJ straw and 100 km in 2015.

Technical development trends and development goals

The energy requirements mentioned here, and the choice of process energy will change by 2050. Progress in efficiency is possible, but above all the use of alternative energy carriers. The use of wood fuels instead of natural gas for drying is already widely implemented today, and by 2030 it can be assumed that only biomass will be used as an energy source (also for electricity from CHP). With regard to efficiency, only little potential can be assumed, as the technologies involved are very robust (mechanical processing, drying)

Current importance and outlook for 2030/2050

Straw is one of the classic residues in agriculture with a comparatively high volume, but only a small part of it has been used for energy production so far. Compared to other agricultural residues, however, there are a relatively large number of studies that consider its potential.

It should be noted that energy use competes with other uses. For example, straw today either remains in the field to fertilise the soil or is used as bedding in animal husbandry. The use of straw as bedding will play an increasing role with the expansion of organic farming. However, cascading use, such as using straw as bedding and then in a biogas plant, can still provide many areas with an adequate supply of straw. The fermentation residues from biogas plants can also be used again as fertiliser. In addition, in some regions the straw volume is so high or the straw requirement so low (including humus reproduction) that material or energy use is possible. However, with the quantities of straw described as available, the primary use objective in all studies is energy production, with a focus on thermal use. Alternative future use approaches can be found at (Trän 2015), where the use as fuel in the transport sector is also considered.

For a future analysis of potentials, not only the number of animals must be taken into account quantitatively but also the type of husbandry. Organic farming in particular has a higher demand for straw in livestock farming. In addition, there are the effects that the straw yield in organic farming is lower compared to conventional farming.

Based on the study "Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem (Elektrizität, Wärme und Transportsektor)" (BioRest (2019)), the future potentials of two models are used in the sense of mapping a use corridor that can be developed in principle. The "BAU" and "With Extended Restrictions" models are described at the beginning of Chapter 2.2.2

For 2015, a residual potential for straw of around 13 million tonnes is assumed. In the case of straw, the areas under cultivation are decisive for the later potential for residues. Future targets such as rewetting can only be estimated with greater effort, since the areas not yet designated today need to be estimated in terms of the amount of grain grown on them. Only assumptions can be made here about the development of the share of organic farming. According to the BMEL, the current target is to achieve a 20% share of organically farmed land. Taking into account current developments in organic farming, it is assumed that only a maximum of 10% of the total area will be organically farmed in 2020. By 2030 the target 20% should be reached.

The UBA studies „Germany in 2050 – a greenhouse gas-neutral country“ and its successors "Ways to achieve resource-saving greenhouse gas neutrality – RESCUE" assume that biomass will no longer be used for energy in 2050. Nevertheless, the ecological effects are quantified in this study.

Technological parameters

The following technological and economic parameters represent the basic cases Supply of straw bales and pellets. A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Energy consumption for recovery	MJ /MJ Straw	0.012	0.012	0.012
Water content straw	%	14	14	14
Calorific value (LHV) Straw	MJ/kg FM	4	4	4
Bulk density straw bales	kg/m^3	145	145	145
Transport distance straw to the pelletising plant	km	50	50	50
Transportation distance straw to the biogas plant	km	10	10	10
Transport distance straw/pellets to the BtX plant	km	100	100	100
Electrical energy pelletising plant	kWh/t pellets	95	95	95
Water content pellets	%	10	10	10
Calorific value (LHV) Pellets	MJ/kg	17.3	17.3	17.3
Bulk density pellets	kg/m^3	720	720	720

Sustainably usable potentials in Germany according to BioRest (2019)

Technical parameters	**Unit**	**2015**	**2030**	**2050**	**Comment**
Potential Germany Model "Business as Usual"	million $t_{abs. dry}$	13	13	13	Range 9.0 - 11.3
Potential Germany Model "With extended restrictions“	million $t_{abs. dry}$	13	11.1	11.1	Range 9.0 - 11.3

Components

The supply of residual forest wood as BtX raw material includes

- Collection and baling
- Transport
- Pelletising if necessary

References

BioRest (2019). BioRest: Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem, Umweltbundesamt, Texte 115/2019

BioEm: Fehrenbach, H., Köppen, S., Markwardt, S., Vogt, R. (2016): Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm), UBA Texte 08/2016. Umweltbundesamt, Projektnummer 28232. Dessau-Roßlau. 2016

JRC - Joint Research Centre (2014): Solid and gaseous bioenergy pathways: input values and GHG emissions; Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259; JRC Report EUR 26696 EN; Ispra 2014.

Module 32: Organic waste

Technology description

As a rule, the two material flows 'biowaste' (material collected in the organic waste bin as a collection system) and 'green waste' (material in the form of garden and park waste from private and public areas, which is usually delivered to appropriate collection points or recycling plants via a delivery system) are considered under the heading of biowaste and green waste. The theoretical potential results from the approx. 60 – 90 kg/person and year of kitchen waste on the one hand and the 20 - 33 kg/person and year of garden and park waste on the other.

For the purposes of the life cycle assessment, organic and green waste is waste that does not carry any ecological burden until it is transported to be used.

As in JRC (2014) and BioEm (2016), the transport route to the biogas plant is assumed to be 20 km (single route by truck total weight 40 t).

From a technical point of view, the fermentation of biogas is not assumed to be in competition with composting plants since a compost product is still present in the end.

Technical development trends and development goals

With regard to collection and transport, no relevant changes in the future scenarios can be assumed compared to the above-mentioned approaches.

Current importance and outlook for 2030/2050

Bio- and green waste today is either composted, fermented in biogas plants or incinerated together with residual waste if there is no separate collection.

The currently estimated potential of organic residues is cited in BioRest (2019) as up to 4.7 million t_{FM}, that of green waste as up to 5.1 million t_{FM}.

The potentials going beyond this are defined for biowaste essentially by the biowaste and green waste components still contained in the residual waste (residual household waste, bulky waste, household-type commercial waste), which are derived on the basis of waste sorting analyses - some of which are available at specific points.

With regard to the quantities already fermented, Fricke (2012) shows a share of approx. 1.1 million t for 2010. In UMSICHT (2015), the Witzenhausen Institute reports on 81 biogas fermentation plants with a throughput capacity of just under 2 million tonnes. The Biogas Atlas 2014/15 documents 113 plants with an input according to BioAbfV, of which 75 plants with a fermentation capacity of approx. 1.9 million t/a mainly use organic and green waste.

In the study "Availability and Utilisation Options for Biogenic Waste and Residual Materials in the Energy System (Electricity, Heat and Transport Sector) BioRest" (BioRest (2019)), two models are used for the future potential in the sense of mapping a utilisation corridor that can be developed in principle. The "BAU" and "With Extended Restrictions" models are described at the beginning of Chapter 2.2.2

For biowaste, the potential approaches are essentially based on the population, the (empirical) specific collection quantities (kg/E*a), the rate of municipal bio waste collection and the possible collection rates of the biogenic waste currently still in residual waste. A medium- to long-term increase in the quantities of biowaste collected to around 6-7 million tonnes of organic waste seems plausible in the "BAU" model. Expanded restriction criteria for bio waste relate in particular to the avoidance of kitchen/food waste and to the aspect of self-composting. Overall, the "With extended restrictions" model therefore assumes a slightly reduced potential approach in the long term compared to the "BAU" model.

For green waste, most of the potential data deviate only slightly from the actual collection quantities. Self-composting activities (as well as other disposal routes) are kept more or less constant. However, the woody part of the green waste in particular is becoming increasingly interesting as an energy source, so that the handling of green waste - e.g., from a municipal perspective - is better organised. Against this background, the "BAU" model assumes slightly increasing quantities - despite increased (costly) expenditure.

BioRest (2019) assumes in the model "With extended restrictions" that undesirable disposal processes (incineration in the garden, illegal disposal, etc.) can be prevented. Similarly, incentives could be created to avoid the mere dumping of green waste (especially grass clippings) in the garden in the absence of a kitchen garden and to transfer the corresponding material flows to an orderly recycling process. Both can lead to a significant increase in volume, so that the potential approach in this analysis is increased in the long term to up to 6.5 million t_{FM}.

Technological parameters

The following technological parameters are based on JRC (2014), BioEm (2016) and BioRest (2019). A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Water content biowaste	%	60	60	60
calorific value	MJ/kg	4	4	4
Transportation distance biowaste to the biogas plant	Km	20	20	20

Useable potential in Germany according to BioRest (2019)

Technical parameters	**Unit**	**2015**	**2030**	**2050**	**Comment**
Biowaste Potential Germany Model "BAU“	million t_{FM}	4.7	6.5	7.0	BioRest (2019)
Biowaste Potential Germany Model "With extended restrictions“	million t_{FM}	4.7	6.25	6.5	BioRest (2019)
Green waste potential Germany Model "BAU“	million t_{FM}	5.1	5.5	5.5	BioRest (2019)
Green waste potential Germany Model "With extended restrictions“	million t_{FM}	5.1	6.5	7.0	BioRest (2019)

Components

The supply of bio-waste as BtX raw material only includes transport

References

BioRest (2019). BioRest: Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem, Umweltbundesamt, Texte 115/2019

BioEm: Fehrenbach, H., Köppen, S., Markwardt, S., Vogt, R. (2016): Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm), UBA Texte 08/2016. Umweltbundesamt, Projektnummer 28232. Dessau-Roßlau. 2016

JRC - Joint Research Centre (2014): Solid and gaseous bioenergy pathways: input values and GHG emissions; Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259; JRC Report EUR 26696 EN; Ispra 2014.

Module 33: Wood scrap

Technology description

Used wood is industrial wood scrap that is produced in the wood processing and woodworking industry and so-called used wood. The term "used wood" refers to used products made of solid wood, wood-based materials or composites with a predominant wood content.

In Germany, the recovery/disposal of wood waste is legally regulated by the wood scrap Ordinance of 2003, which was last amended on 29.03.2017. It contains requirements for

- the recycling of materials,
- energy recovery and
- the removal of wood scrap.

The term material recycling refers to the processing of wood scrap into wood chips and shavings for the production of wood-based materials, as well as the extraction of synthesis gas for further chemical use and the production of activated carbon or industrial charcoal, etc. Currently, the most widespread way of recycling wood scrap is the production of wood-based materials, in particular the production of chipboard. Wood pyrolysis and wood gasification processes have so far not been of major industrial importance.

Energy recovery involves the use of wood scrap as fuel in installations not requiring a permit. Depending on whether and how contamination is present, wood scrap may be burned in different types of plants with adapted requirements for combustion control and waste gas purification. To ensure that wood scrap can be recycled or used to generate energy without harm, the regulation divides wood scrap into different categories.

Restrictions with regard to the options for use result in particular from the pollution load and thus from the design of the respective wood products and the separability of the different categories of wood scrap at the point of generation or collection. The aim should be - in conformity with the requirements of the KrWG and the hierarchy of use within the framework of the bio-economy strategy - to increase the proportion of material use either through optimised product design or through improved separation techniques (detection methods). For BtX production, wood scrap can essentially be used as wood chips. In JRC 2014 and BioEm 2016, 0.00336 MJ diesel per MJ wood chips (with 30% water content) are used for shredding.

The transport route of wood chips to the BtX plant also depends on their size, which determines the catchment area. For the base case, BioEm (2016) assumes a transport distance of 500 kilometres (with a total weight of 40 t by truck). In this study, the transport distances can be varied according to supply path and location.

Technical development trends and development goals

It can be assumed that the above-mentioned energy requirements and the choice of process energy will change by 2050. Progress in efficiency is possible, but above all the use of alternative energy carriers. The use of wood fuels instead of natural gas for drying is already widely implemented today, and by 2030 it can be assumed that only biomass will be used as energy source (also for electricity from CHP). With regard to efficiency, only little potential can be assumed, as the technologies involved are very robust (mechanical processing, drying).

Current importance and outlook for 2030/2050

The potential derivations in the wood scrap sector are mainly based on data from the state statistical offices and on figures from Mantau (2005, 2010, 2012), which in turn were partly collected on the basis of surveys of the players in the wood scrap market. The main focus was on the market and trade volume. Shares that are still contained in mixed municipal waste, e.g., were hardly ever reported. The study "Availability and options for the use of biogenic waste and residual materials in the energy system (electricity, heat and transport sectors) BioRest" (BioRest (2019) assumes a current potential of 6.7 million tonnes, but the range between different studies is quite wide).

For future potential, BioRest (2019) considers two models in the sense of mapping a basically accessible use corridor. The "BAU" and "With extended restrictions" model are described in this report at the beginning of

Chapter 2.2.2
The "BAU" model assumes that it will be possible to increasingly separate the wood components (approx. 3 million tonnes) currently still contained in mixed municipal waste (including effects from the 2017 Ordinance on Commercial Waste). A collection rate of 50% is assumed in this respect (rest: e.g., wood that is difficult to separate as part of composites). The material use share is only slightly increased due to the additional separated wood scrap that is mainly contaminated/treated.

The model "With extended restrictions" identifies two possible lines of development. On the one hand, shifts in the use of raw wood would increase the potential-forming wood scrap base through increased material use (at the expense of raw wood use for energy purposes) within the meaning of the Wood Charter 2.0. On the other hand, an appropriate product design and optimised technologies/mechanisms for separating wood scrap (by quality) could increase the material use of wood scrap. However, both presuppose the availability of corresponding markets. Therefore, the possible share of material use that can be sold on the market is cautiously estimated at approx. 2.0 million tonnes.

Technological parameters

The following technological parameters represent the base case from JRC 2014 and BioEm 2016 for the production of wood chips from wood scrap. A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Energy consumption shredding	MJ /MJ wood chips	0.00336	0.00336	0.00336
Water content wood chips for end use	%	30	30	30
Calorific value (LHV) wood chips (humidity 30%)	MJ/kg	12.3	12.3	12.3
Bulk density wood chips (moisture 30%)	kg/m^3	220	220	220
Transport distance wood chips to the BtX plant	Km	100	100	100

Sustainably usable potentials in Germany according to BioRest (2019)

Technical parameters	**Unit**	**2015**	**2030**	**2050**	**Comment**
Potential Germany Model "Business as Usual"	million t	7.2	9.0	9.0	BioRest (2019)
of which materially used	million t	1.4	1.8	1.8	BioRest (2019)
Potential Germany Model "With extended restrictions	million t	7.2	9.0	9.0	BioRest (2019)
of which materially used	million t	1.4	2.3	2.3	BioRest (2019)

Components

The supply of wood scrap as BtX raw material includes

- Chipping
- Transport

References

BioRest (2019). BioRest: Verfügbarkeit und Nutzungsoptionen biogener Abfall- und Reststoffe im Energiesystem, Umweltbundesamt, Texte 115/2019

BioEm: Fehrenbach, H., Köppen, S., Markwardt, S., Vogt, R. (2016): Aktualisierung der Eingangsdaten und Emissionsbilanzen wesentlicher biogener Energienutzungspfade (BioEm), UBA Texte 08/2016. Umweltbundesamt, Projektnummer 28232. Dessau-Roßlau. 2016

JRC - Joint Research Centre (2014): Solid and gaseous bioenergy pathways: input values and GHG emissions; Calculated according to the methodology set in COM(2010) 11 and SWD(2014) 259; JRC Report EUR 26696 EN; Ispra 2014.

Module 34: Silage maize

Cultivation description

Silage maize is an annual C4 plant which is characterised by high biomass yields and relatively low water and nutrient requirements. It has long been established as animal feed and since 2004/2005 has been increasingly used for biogas production. The end use is not important for the selection of the varieties.

In terms of cultivation, maize is characterised by low soil requirements and good self-fertilisation and fertiliser compatibility. Due to its good self-tolerance, high percentages can be achieved in crop rotation, depending on the location. However, maize cultivation also presents risks. There is an increased risk of erosion due to wide row spacing and late soil cover. In addition, good fertiliser tolerance can lead to over fertilisation and thus to high nutrient yields (especially Nitrate leaching).

The time of harvest is determined by the optimum dry matter content for silage. This is between 30% and 33%. Harvesting is done with a forage harvester. As only roots and stubble are left behind during harvesting, a sufficient humus content must be ensured by crop rotation. The harvested material is then ensiled, whereby lactic acid fermentation produces a long-lasting substrate (FNR 2017a, DMK 2017).

Technical development trends and development goals

An important prerequisite for increasing the area under maize was the development of hybrid maize in the 1950s. Since then, many breeding programmes have been established over the past 15 to 20 years. This has enabled maize cultivation to advance into areas with increasingly unfavourable climatic conditions, and yields have risen from around 75 dt DM/ha to over 160 dt DM/ha.

In addition to yield increases, breeding also focuses on traits such as early maturity, stability, juvenile development or cold tolerance in spring, resistance or tolerance to pests and diseases, and feed quality (DMK 2017).

Current importance and outlook for 2030/2050

Maize is the second most important crop in Germany after wheat, with silage maize occupying by far the largest area. Most of it is in turn used as animal feed, and its use in biogas plants is in second place. Silage maize is the most important plant in biogas production. In 2016, 1.6 million hectares were cultivated as fodder and 1 million hectares for use in biogas plants. Since 2007 (cultivation to 0.1 million ha) there has been a sharp increase in the area under biogas maize, but this has declined significantly since 2012 due to changes in the legal framework (FNR 2017a). Within Germany, maize cultivation is particularly concentrated in regions with high animal husbandry (DMK 2017). This has far-reaching ecological effects, as biogas fermentation residues are spread on the fields in addition to animal manure. This causes nitrogen surpluses, which lead to increased nitrate levels in groundwater and negative effects on biodiversity.

At European level, there was a slight increase in silage maize cultivation areas and an expansion of biogas plants (EBA 2016). However, there is no information available on the use of silage maize in biogas plants. The future development of cultivated areas is closely linked to the further development of bioenergy and the role of biogas.

A further increase in yields is expected by 2050. Compared with [UBA, 2014], a more conservative growth rate of 1.1 is assumed here, with linear development assumed. For fertilisation, an increase in efficiency of 11% is assumed [UBA, 2014]. However, the increase in fertilisation efficiency is partly offset by the increase in yield.

Technological parameters

In the current project the following specifications are assumed. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Income	t FM / ha*a	44	45	48

Mineral N fertilizer	kg N / ha*a	68	68	66
P_2O_5 fertilizer	kg P_2O_5 / ha*a	41	41	40
CaO fertiliser	kg CaO / ha*a	300	308	330
K_2O fertiliser	kg K_2O / ha*a	26	26	25
Fermentation residues	kg N / ha*a	133	136	146
Pesticides	kg / ha*a	7	7	8
Fuel requirements (soil cultivation, harvesting, ensiling)	l / ha*a	43	43	43
Silage losses	%	10%	10%	10%

Components

Maize cultivation comprises the following elements:

- Soil cultivation
- Sowing
- Fertilisation, plant protection measures
- Harvest at approx. 35% DM content with maize chopper
- Ensiling

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Module 35: Short rotation coppice

Cultivation description

Different fast-growing wood types are summarised under energy wood. These include poplar, willow, robinia and ash as the most common tree species. Poplars and willows are usually grown in so-called short-rotation plantations. In addition to the various tree species, numerous varieties or clones are available to be able to make a selection optimally adapted to the site conditions. All approved poplar varieties are listed in a poplar register of the Federal Agency for Agriculture and Food (BLE).

In Germany, willows and poplars are cultivated as pure or mixed crops, but these areas do not legally become forest if the trees are harvested at least once within 20 years. If grassland is used for cultivation, it is legally considered as grassland conversion and the status changes from grassland to permanent crop.

Cultivation takes place on regular arable land or on marginal and special areas, such as landfill or conversion areas. To prepare the area, it is treated with a total herbicide and the area is ploughed over. In spring, the seed bed must be prepared in a fine-crumbling way. Planting is usually done with cuttings (approx. 20 cm), which are inserted 20 to a maximum of 50 cm into the soil. For smaller areas (up to 0.5 ha) this is done by hand, for larger areas with a planting machine. The planting unit is single-row (1,500 - 8,000 pcs.) or double-row (40 - 80 pcs. in a row) with a tramline in between (2.5 - 3 m, approx. 13,000 pcs/ha). In the year of planting, the cuttings must be kept as weed-free as possible, and mechanical or chemical control is recommended. No further measures are necessary after that. Fertilisation is only necessary if the area has a nutrient deficiency (e.g., Post-mining landscapes). On average arable land, nutrient deprivation during harvesting is compensated by the leaves remaining as the most nutritious tree components. While in the case of poplar, fertilisation can thus be dispensed with for at least the first 15 years, N-fertilisation can lead to a certain yield increase in pasture. For both tree species a P/K compensatory fertilisation is applied at the level of the depletions that have taken place with the wood.

The energy woods count as so-called permanent crops, which can be used for about 20 years with several harvest cycles. With regard to the rotation periods, a distinction is made between short (3-5 years), medium (6-10 years) and long (>10 years) rotation periods. In the case of short rotation periods, harvesting takes place with full harvesters, which immediately process the wood into chips. In this case, subsequent drying of the harvested material is usually necessary, either by storage without heat input or by using waste heat. For medium and long rotation, forestry equipment is used and harvesting takes place in four separate steps (felling, back, trunk storage, chipping). The up to three times higher harvesting costs are compensated by the better quality of the wood or wood chips and higher yields per hectare. Wood used for energy production tends to be produced with short rotation times, while the long rotation times are used to obtain wood used as a material. After harvesting, the trees sprout again from the remaining stock.

After the end of the period of use, short rotation coppices must be cultivated in such a way that they are suitable as arable land for annual crops. For this purpose, after the last harvest, the area is worked with forestry mulchers and then milled 20 to 30 cm deep. (Forest21 2017, FNR 2017, Becker et al., 2014)

The wood from short-rotation plantations can be used for the production of BtX energy carriers both as wood chips and as wood pellets. The additional expenses for transport to the pelletising plant and for Pelletising are described in detail in Module 29: Forest residual wood

Technical development trends and development goals

Different varieties are available for cultivation. However, according to [Gaul, 2010], there are still too few of them for optimal coverage of all locations and there is also a lack of experience regarding the right combination of variety and location. Furthermore, many varieties of poplar in particular have been bred for use in forests. There is therefore a need for further development in this area. However, according to [Wühlisch, 2016], research funding was reduced at the same time as cultivation stagnated.

Current importance and outlook for 2030/2050

In 2015, energy wood was produced in SRC on approx. 7,000 ha, whereby no expansion of the area was apparent in the period between 2012 and 2015. This is a contrary trend to the reporting period between 2008 and 2011, when a clear upward trend was evident [Wühlisch, 2012]. There are many reasons for the stagnation, with low profitability and the long commitment of space being the most important. When short-rotation plantations are cultivated on arable land, they are in direct competition with economically more attractive cultivation options. Here, the cultivation of maize for biogas plants is the first priority. In addition, the ploughing up of grassland is prohibited and SRCs are only slightly considered as ecological priority areas in agricultural subsidies [Wühlisch, 2016].

On the utilisation side, energy wood is mostly used in heat production, although it currently plays a very minor role compared to other raw materials. Mainly logs are used here in the private sector, as well as pellets and wood chips from forest residues, the latter having a high import rate. Future SRC area development therefore depends on how the demand for energy wood develops and whether this demand can be adequately met from the forest. If the biomass is produced in sufficiently large quantities, pelleting is also possible. If further technical establishment is achieved, SRC wood can also be used in processes for gasifying the wood biomass (pyrolysis) or for liquefying the energy carriers (Fischer-Tropsch process). Overall, however, cultivation is likely to remain limited to niche areas (such as conversion areas) in the future.

At European level, too, the size of the area under cultivation is falling short of expectations. Currently, short rotation coppices are grown on about 50,000 ha. The most important growing areas are in Sweden, Denmark, Poland and Germany. The same pattern can be seen everywhere, with large areas being established within a short period of time, but then declining again [Lindegaard et al., 2016].

With regard to yields, a further increase is expected by 2050. As in [UBA, 2014], a growth rate of 1.3 is assumed, with a linear trend. The growth rate is relatively high, since short-rotation plantations are not yet well established and therefore disproportionate breeding successes can be expected. An efficiency increase of 11% is assumed for fertilisation [UBA, 2014]. However, the increase in fertilisation efficiency is partly offset by the increase in yield.

Technological parameters

In the current project the following specifications are assumed. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Income	T TM / ha*a	10	11	13
Diesel requirements	l / ha*a	46	46	46
Pesticides (total first and last year)	Kg / ha*a	3	3	3
N-fertiliser (organic)	Kg N / ha*a	37	39	43
P_2O_5 fertilizer	kg P_2O_5 / ha*a	6	6	7
K_2O fertiliser	kg K_2O / ha*a	25	26	29
Electrical energy Pelletising	kWh / t pellets	237	237	237
Heat requirement Pelletising	MJ / t pellets	3200	3200	3200

Components

The cultivation of energy wood comprises the following steps:

- Establishment of the SRC with cuttings (every 20 years) and chemical weed control
- Moderate fertilisation; no pesticides from the 2nd year onwards
- Harvest every 3 - 5 years with full harvesting machines (simultaneous harvesting and chopping)
- Harvest at 50% DM content
- Drying of the wood chips in the air or with waste heat

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Module 36: Miscanthus

Cultivation description

Miscanthus (also called Chinese reed or elephant grass) is a perennial fast-growing C4 grass with high biomass yields. In Europe, the variety *Miscanthus x giganteus* is usually cultivated. Its location requirements are comparable to those of maize, but propagation is via rhizomes. After planting, it can be harvested from the third year onwards for up to 20 years without further tillage.

Miscanthus can be grown on all soils suitable for maize. It requires a good water supply, while waterlogging and compacted soils should be avoided. In general, it has good tolerance to cold and low tolerance to heat and drought. However, there is a risk of too low temperatures in the first winter (FNR 2017, Pude 2012, Energiepflanzen.com 2017).

The planting is done with a vegetable planting machine. There is no harvest in the year of planting, in the 2nd year a reduced harvest and from the 3rd year onwards, it is possible to harvest in full annually for up to 20 years. Harvesting takes place in the winter months after the growth has died and the leaves have fallen off. A maize chopper can be used for the harvest. Subsequent drying is not necessary. The crop is either pressed into bales or pellets, or it is transported loose as chopped material. As only one variety is well established, there are large yield fluctuations of 10 to 25 t DM/ha depending on location factors. Very high yields can be achieved with irrigation, particularly in southern Europe [Lewandowski et al., 2000].

The plants require only a small amount of fertiliser (see chapter "Technological parameters"), as the nutrients are shifted to the rhizomes in winter. In addition, nutrients enter the soil through the leaves remaining on the field. No fertilisation should be applied during the year of planting, after which small amounts of N fertiliser can be applied. Fertilisation can also be done using fermentation residues, liquid manure or ash.

Weed control is only necessary in the first few years. The herbicides commonly used in maize cultivation can be applied. Problems with diseases or pests are not known (FNR 2017, Pude 2012, Energiepflanzen.com 2017).

After the utilisation phase, the area is made usable again for annual arable crops by deep digging or milling. In addition, the area should be treated with a total herbicide.

Today, Miscanthus is mostly used for thermal utilization in large combustion plants, combined heat and power plants or in biomass heating systems. Due to the high ash content, however, special straw heating boilers or biomass furnaces for stalk material have to be used.

In the future, Miscanthus could be used for the production of BtX energy carriers both chopped and pelletised. The additional costs for transport to the pelleting plant and for pelleting are described in detail in the module Straw.

Technical development trends and development goals

Although cultivation trials have been underway in Europe for many decades, only one well-established variety is available to date, and its final yield varies greatly between different locations. There is also a lack of reliable recommendations on fertilisation and harvesting machines that are precisely adapted to the characteristics of Miscanthus [Lewandowski et al., 2016].

Breeding trials aim to develop new varieties that are suitable for different locations and have better frost resistance [Lewandowski et al., 2000].

Current importance and outlook for 2030/2050

Miscanthus is currently only grown on 20,000 ha in Europe, with the main areas of cultivation in England, France, Germany, Switzerland and Poland [Lewandowski et al., 2016]. In Germany, Miscanthus is cultivated on around 4,500 ha, although the trend is declining (FNR 2017).

There are many reasons for the low distribution and declining cultivation trend. High production costs and low yields are considered the main obstacles. The high costs arise in the establishment of a new plantation, which must be carried out using expensive rhizomes. On the other hand, the production of electricity and heat is an application that generates only small revenues. There is no firmly established market, so the hurdle of a long-term investment (the initial costs are only amortised after 10 - 25 years) is high (Lewandowski et al., 2016). It is also indicative of the low significance that no standard value was derived at European level under the Renewable Energy Directive (2009/28/EC). The reason for this is the inadequate database [Giuntoli et al., 2017].

At European level, a cultivation potential of 10% of the utilised agricultural area has been certified [Hastings et al., 2009]. Good growing areas tend to extend to the south, where good yields can only be achieved with irrigation. In northern Europe (apart from England), there is a risk that planting will not survive the first winter, which is one of the main barriers to the spread of cultivation northwards (Lewandowski et al., 2000).

The future spread of Miscanthus will depend on the development of the energy markets. Miscanthus can only be grown on arable land and therefore competes with other profitable food and feed crops. It is not profitable to grow it on marginal sites due to low yields. Miscanthus is therefore dependent on subsidies, similar to the establishment of other bioenergy crops in Europe. In addition, it competes in its application with residual wood from forestry and residual wood from the wood-processing industry. Both are available in large quantities and are profitable even without subsidies. Its future role will also depend on whether higher value material marketing options can be established (Lewandowski et al., 2016).

A further increase in yields is expected by 2050. Here, as in (UBA 2014), a growth rate of 1.3 is assumed, with a linear development. The growth rate is relatively high, since Miscanthus is not yet well established and therefore disproportionate breeding success can be expected. An efficiency increase of 11% is assumed for fertilisation (UBA 2014). However, the increase in fertilisation efficiency is compensated by the increase in yield.

Technological parameters

In the current project the following specifications are assumed. A complete list of the technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Income	t TM/ ha*a	15	16	20
Mineral N fertilizer	kg N / ha	50	52	58
P_2O_5 fertilizer	kg P_2O_5 / ha*a	50	52	58
K_2O fertiliser	kg K_2O / ha*a	100	104	106
Pesticides	Kg / ha*a	2	2	3
Fuel requirements	l / ha	37	37	37
Power consumption pelletising	kWh / t pellets	103		

Components

The cultivation of Miscanthus involves the following steps:

- Establishment of planting (every 20 years) including chemical weed control
- Annual harvest Maize choppers (at >80% DM content), pelleting if necessary

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2.2.3 Carbon sources

The production of synthetic liquid and gaseous hydrocarbons on the basis of renewable electricity (power-to-gas (PtG), power-to-liquid (PtL)) requires carbon sources. In addition to the carbon contained in biomass, CO_2 in waste and flue gases is a particularly suitable source. Possible CO_2 sources are also biogas plants, industrial processes and fossil power plants. But carbon dioxide can as well be extracted from the ambient air. Data for CO_2 capture from biogas were compiled mainly on the basis of the JOANNEUM RESEARCH project “Biogas Gesamtbewertung” funded by the Austrian Research Promotion Agency[5] and the DBFZ Report No.26[6] as the latest study relating to Germany. Data for CO_2 capture from industrial waste gases, fossil power plants and the air[7] were available to DLR from its own research projects. In addition, ifeu data from the projects "sunfire", "CORAL" and "Kopernikus" (all BMBF)[8], as well as available data on existing plants[9], were included. Further sources are listed in the respective modules.

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CO_2 capture from biogas, industrial processes, fossil power plants and air

Module 37: CO_2 capture from the air

Module 38: CO_2 capture from biogas without heat demand

Module 39: CO_2 capture from biogas with heat demand

Module 40: Selexol physical capture

Module 41: Rectisol physical capture

Module 42: Amine capture MEA

Module 43: Amine capture MDEA

Module 44: Potassium carbonate capture

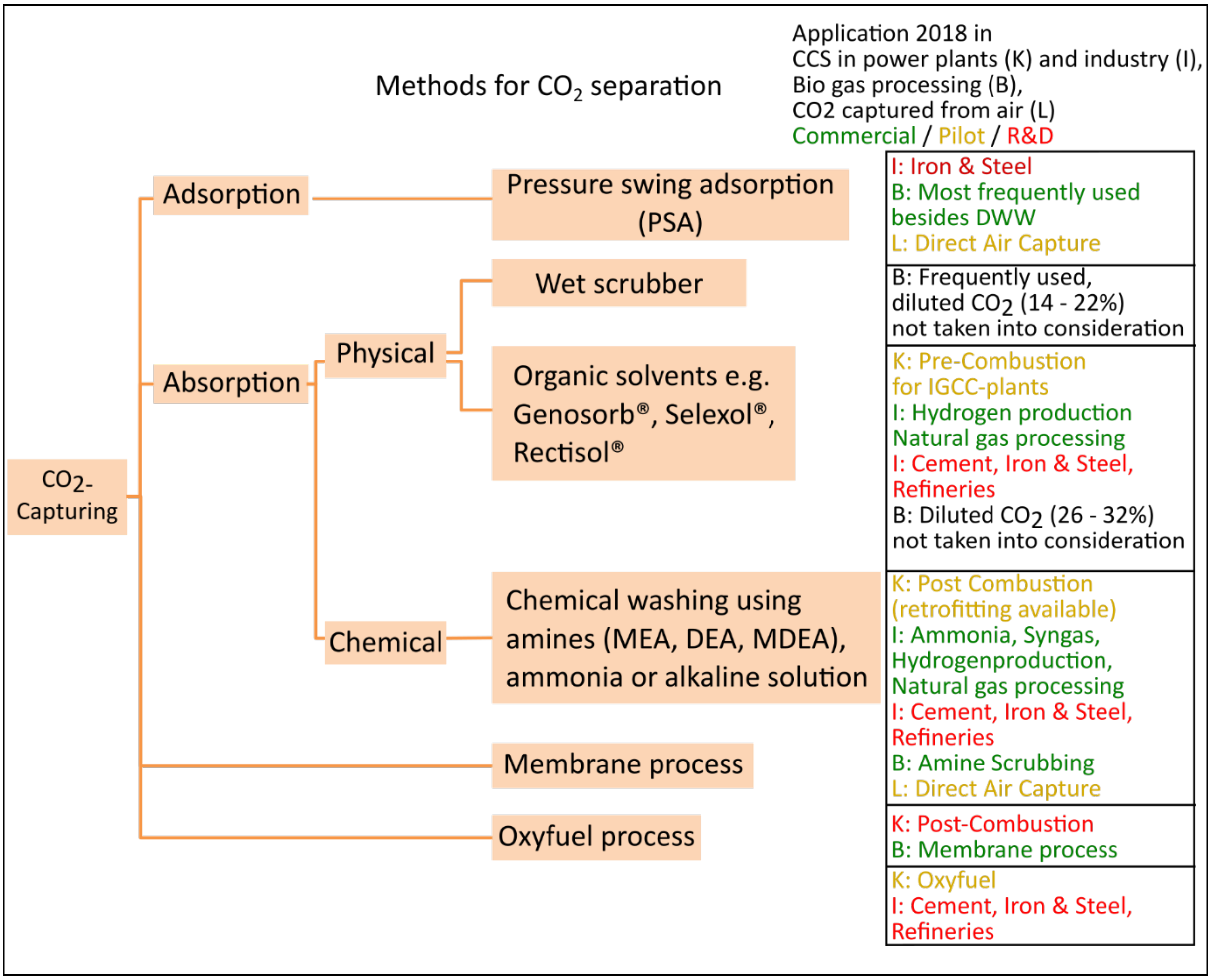
Module 45: Power plant flue gases (Oxyfuel)

Technology description

This fact sheet describes technologies for the capture of CO_2 in biogas upgrading, for capture in industrial processes and fossil power plants, and from the air. As in biogas upgrading (described in the module 13 to 17 description), CO_2 capture from industry, power plants and air must be recorded with its energy and material costs. The system boundary of the modules begins with the delivery of the raw gas or air and ends before the intermediate storage of the captured CO_2.

The following figure provides an overview of available CO_2 capture processes. It also shows the state of development of the technology in the respective fields of application. A basic distinction is made between adsorptive, absorptive and membrane processes. Details on these processes are described in the description of modules 13 to 17. Another technology that can be used in industry and power plants is the concentration of CO_2 when combustion takes place with pure oxygen (oxyfuel process).

Figure 17: Overview of CO_2 capture processes



Source: own figure, JOANNEUM RESEARCH, based on (FNR 2014, Markewitz 2017)

The composition of the raw gas and the CO_2 content, the amount of CO_2 to be captured and location criteria (e.g., available heat source) determine the choice of the capture technology. The individual processes and their advantages and disadvantages are presented below (FNR 2012, FNR 2014, Billig 2016, Güssing 2018, TU Vienna 2012, DENA 2018, NTEL 2013, Koytsoumpa 2015, Urech 2013, Schäffer 2013).

Pressure swing adsorption (**PSA**) is an adsorptive separation process. Adsorption is the adhesion of gas components (here: CO_2) under pressure onto the surface of solids (adsorbents). Activated carbons, zeolites or carbon molecular sieves can be used as adsorbents. Before adsorption, sulphur and water vapour must be removed from the raw gas in the case of high H_2S contents, as these substances can damage the activated carbon used in the adsorption process. Pressure swing adsorption is a process that is particularly suitable for smaller plant capacities and is therefore the most frequently used process in biogas upgrading alongside pressurised water scrubbing. In the so-called lean gas as waste gas from biogas treatment, the CO_2 content is up to 87-99 vol-% (FNR 2014): thus, the DWA is also suitable for the goal of CO_2 capture. Pressure swing adsorption is also one of the most advanced processes for separation from air. In demonstration plants in Switzerland and Germany, the air is first passed through the adsorption chamber, where the CO_2 attaches itself to a pulp granulate. The desorption then occurs at reduced pressure and a temperature of approx. 100 °C (Climeworks 2017a). In the power plant sector, the process is not relevant, but for industry (steel and iron) it is mentioned as a possible option for the future (after 2030).

Advantages: Dry process - therefore no wastewater, no or only little heat necessary, waste heat usable (compression to 6-10 bar causes heating from 2535 °C to 6090 °C), proven commercial technology

Disadvantages: high electricity demand for compression and expansion, high costs for adsorbents, also for their disposal, relatively high methane losses in biogas treatment.

Pressurised water scrubbing (PWS) is an absorptive CO_2 capture process. In contrast to adsorption, absorption is the dissolving of gases in liquids (absorbent). In pressurised water scrubbing, only water is used as an absorbent. The process is based on the reversible absorption by physical binding forces (physisorption) of CO_2, but also of other acidic (e.g., H_2S) and basic (e.g., ammonia - NH_3) gas components in water. This process is currently the most frequently used in biogas treatment. Since the CO_2 in the lean gas is diluted with stripping air and has a share of 14-22 vol-%, PWS is not considered further for the goal of CO_2 capture. For power plants, industrial plants and air separation, PWS is not relevant.

Physisorption with organic solvents is similar to pressurised water scrubbing. However, the solvent used for absorption is not water but an organic solvent (e.g., Genosorb™ for biogas treatment, Rectisol® or Selexol® for CCS in industrial processes). A major advantage over PWS is the much greater solubility of CO_2. Therefore, compared to water, considerably less scrubbing liquid is required to capture the same amount of CO_2 and the energy required for liquid circulation is lower. The desorption of the solvent takes place via pressure relief and requires heating (except with Selexol®). This process is mainly used in industry for natural gas processing, ammonia, synthesis gas and hydrogen production. It can also be used as a pre-combustion process after coal gasification in coal-fired combined cycle power plants (IGCC). However, since it is not suitable as a retrofit measure for coal-fired power plants, it is of no relevance to Germany. In contrast to chemical absorption, the physical absorption process is mainly used at CO_2 partial pressure of more than 10 bar. This process does not play a role in biogas treatment or separation from air.

Advantages: lower electricity demand than PWS, proven commercial technology, lower methane losses in biogas treatment compared to PWS and DWA, no pre-desulphurisation necessary, long solvent resistance

Disadvantages: higher costs than PWS for operating materials and disposal, heat input for desorption

Chemical absorption or amine scrubbing is characterised by the fact that physical absorption, the dissolution of the gas in the liquid, is followed by a chemical reaction between the dissolved gas component and the scrubbing liquid within the liquid phase. As a result, the binding of the gas components to the scrubbing liquid is significantly stronger and thus the loading capacity of the liquid is many times higher than with pure physical absorption. The chemical reaction takes place very selectively, whereby e.g., the absorption of methane into the liquid can be reduced to a minimum. Thus a very high CO_2 yield and a very low methane slip can be realised. Due to the high affinity of carbon dioxide to the solvents used (mainly aqueous solutions of monoethanolamine MEA, diethanolamine DEA and methyldiethanolamine MDEA, K_2CO_3), the operating pressure of these plants can be selected significantly lower than in comparable plants with pressurised water scrubbing. This process is mainly used in industry as a standard process in natural gas treatment. It can also be used as a post-combustion process in coal-fired power plants. Compared to physical absorption, the physical absorption process is mainly used at CO_2 partial pressure below 10 bar. For separation from the air, processes are tested with scrubbing solutions containing caustic soda (NaOH), caustic potash (KOH) or calcium hydroxide ($Ca(OH)_2$). This produces a carbonate, for example sodium carbonate (Na_2CO_3). CO_2 can be dissolved from this carbonate with the help of an acid. One way of subsequently restoring the caustic solution and the acid is calcination, which is known from the paper industry. It can be carried out using various methods, but ultimately CO_2 is released from its carbonate compound by a thermal process. (Goeppert et al., 2012, Socolow 2011). In biogas upgrading in Germany, chemical scrubbing is of similar importance as DWA and PWS, and due to the CO_2 content of 99 vol-%, the process is also important for CO_2 capture.

Advantages: very selective scrubbing, low methane slip in biogas upgrading, proven commercial process

disadvantages: amine solutions are partly hazardous to the environment (water), high heat requirement for desorption, high costs (depending on the solvent for the plant, equipment, disposal), partly corrosion protection necessary

The **membrane separation process is** based on the principle of separating CO_2 and the other gas components by the different permeabilities of the different sized gas molecules through the membrane (metallic, ceramic or polymer-based). The separation of carbon dioxide and other gas components is the more effective, the larger the membrane surface area, the smaller the membrane thickness, the higher the partial pressure difference and the higher the selectivity of the membrane for the different gas components. The process has so far only been used sporadically in biogas upgrading in Germany. The combination of biogas upgrading to biomethane and CO_2 capture requires a two-stage process with membranes of different permeance or selectivity. As a post-combustion process for power plants and industry, membrane technology is inferior to chemical absorption: Due to the relatively low CO_2 concentration in the flue gas, the low concentration gradient as driving force of the process is disadvantageous. The combination of the membrane process with an absorption system is promising. This process is not suitable for separation from air.

Advantages: no operating resources required - resulting in low costs in operation, simple process control, high environmental friendliness in operation without chemicals

Disadvantages: high power consumption, high system costs

The term oxyfuel refers to the combustion of carbonaceous fuels with pure oxygen, which results in a high concentration of carbon dioxide. Compared with today's coal-fired power stations, where the CO_2 content of the flue gas is about 12 to 15% by volume, the CO_2 content of oxyfuel plants is about 89%. Condensation of the water vapour produces a flue gas which consists almost entirely of CO_2 and which can be transported directly to the storage site after compression. Oxygen for the combustion process is provided by an air separation plant. Currently there are no large-scale oxyfuel demonstration plants worldwide. Potential exists in power plants as well as in the cement industry.

Technical development trends and development goals

Biogas treatment

Development goals for **pressure swing adsorption** are the further reduction of the relatively high methane slip and the reduction of electricity consumption. Currently only larger plants are economically viable (>500 Nm^3/h biomethane). The development objective is therefore also to reduce the treatment costs for smaller plant capacities for decentralised CO_2 capture. However, the process of processing to biomethane only contributes a small proportion of the total production costs. The predominant share of the costs of biomethane is in the production of raw biogas, which has a comparatively low cost reduction potential (Billig 2016).

In **amine scrubbing,** heat recovery is at the centre of development. The use of amino acid salts as an alternative to amines is also a research objective. The advantage would be lower process temperatures for the regeneration of the scrubbing solution to enable the process for efficient CO_2 capture even for smaller biogas plants.

The development goal of the **membrane process** is to reduce the polymer-specific volume resistance by means of new materials and to achieve technically interesting flow rates and thin yet stable membranes.

The technological parameters were left unchanged for 2030 and set for 2050 on the basis of the following assumptions: The methane yield as the main product of biogas upgrading increases by 10% due to new bacteria - thus the amount of CO_2 separated decreases accordingly.

Large-scale CO_2 capture

CO_2 capture with **chemical scrubbing has** been used for about 80 years. The technologies listed are state of the art and do not expect any further major technological leaps. If necessary, an increase in efficiency can be achieved by changing the mixing ratio in amine scrubbing, but this depends on the composition of the flue gas. The **membrane process** has been used for natural gas treatment since the 1980s. A first demonstration plant for flue gas cleaning was commissioned in the USA in 2014. Challenges include the low pressure and the complex flue gas composition which can lead to membrane fouling and clogging. The potentials are characterised by high energy efficiency and environmental friendliness as no chemicals are used. If an **Oxyfuel burner** is used in a new cement plant, the subsequent CO_2 capture can be operated much more efficiently and thus more cost-effectively (Kuramochi 2012).

Separation from the air

There are now a few pilot and demonstration plants for the capture of CO_2 from the air. In Canada, Carbon Engineering operates an absorption pilot plant based on NaOH and KOH with a capacity of one tonne of CO_2 per day. Currently the extension to a PtL pilot plant is planned. The first commercially available demonstration plant for the recovery of CO_2 from the air using an adsorption process is manufactured and operated by Climeworks. The Climeworks technology has been used in a BmBF-funded PtL pilot plant in Dresden since 2014 and is to be used in a commercial PtL plant in Norway from 2020. As the different separation variants have only recently been used on a demonstration scale, there is still a lot of room for further technical developments. In particular, the development of new adsorption materials could make the separation process much more efficient. The minimum energy requirement theoretically achievable is given in the literature as about 1 GJ/tCO_2. The current processes are more likely to be 6-9 GJ/tCO_2 (Socolow 2011).

Current importance and outlook for 2030/2050

Biogas treatment

In Germany only about 150 CO_2 capture plants are in operation as biogas upgrading plants (Liebetrau 2017), in whole Europe about 250 with the main countries Germany, Sweden and the Netherlands. Great Britain, France and Italy are seen as countries with high potential, especially for the use of residual materials (Weber 2015). In Germany, pressure swing adsorption and amine scrubbing are the dominant treatment processes in the plant portfolio and are relevant in combination with CO_2 capture (Dunkelberg 2015).

Biomethane as a renewable energy source is considered to have a significant potential as an energy carrier that can be stored in the gas grid and thus used in a wide range of applications, as it allows flexible use in the electricity, heat and mobility sectors. In the future, a coupling of biogas processing with Power to Gas (PtG) could become interesting. In this way, the CO_2 from the flue gas of biogas upgrading could also be methanised and fed into the gas grid (Sterner 2010).

Large-scale CO_2 capture

Physical scrubbing with Selexol® or Rectisol® is widespread, as well as chemical scrubbing (especially amine scrubbing) and common plant modules (Kohl 1997). Today, power plant waste gases account for the largest share of CO_2 emissions (≈79%), followed by the cement industry (≈7%), refinery (≈6%) and steel industry (≈5%). Hence, there is a very large market potential, especially for the use of chemical scrubbers for power plant flue gases. However, it must be taken into account that fossil power plants will be reduced step by step in the course of a transformation to a climate-neutral economy. In all probability, however, process-related CO_2 emissions will still be generated in the cement industry in 2050.

Separation from the air

The extraction of CO_2 from air has no commercial significance at present. As long as CO_2 is produced in greater concentration elsewhere, the energetic and technical effort is not worthwhile in the foreseeable future. However, the situation may be different in the future if, on the one hand, larger quantities of carbon are required for PtX production, and, on the other hand, point sources such as power stations or industrial plants emit less and less CO_2 and the biogenic CO_2 sources are limited. In addition, airborne capture could enable the use of large but remote wind and solar power potentials for the production of PtX energy carriers.

Technological parameters

Biogas treatment

The following technical parameters refer to reference plants already selected and described in modules 11 and 12 (biomass fermentation). The technological parameters were left unchanged for the year 2030 and set for the year 2050 based on the following assumptions: The methane yield as the main product of biogas upgrading increases by 10% due to new bacteria; thus the amount of CO_2 captured decreases accordingly.

CO_2 capture from biogas without heat demand (based on DWA, PWS)

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Operating hours	h/a	8,400	8,400	8,400
Plant capacity Biogas upgrading	Nm³/h Biogas	1,400	1,400	1,400
CO_2 volume flow CO_2 from biogas/lw. raw and residual materials	t/a CO_2	10,478	10,478	9,838
CO_2 volume flow CO_2 from biogas/bio-waste	Nm³/h CO_2	9,314	9,314	7,917
CO_2 content Mean value 87-99%	%	93	93	93
Specific energy demand *	kJel, th/kgCO_{2cap}	-	-	-

CO_2 capture from biogas with heat demand (based on amine scrubbing)

Technical parameters	Unit	2015	2030	2050
Operating hours	h/a	8,400	8,400	8,400
Plant capacity Biogas upgrading	Nm³/h Biogas	1,400	1,400	1,400
CO_2 volume flow CO_2 from biogas/lw. raw and residual materials	Nm³/h CO_2	10,478	10,478	9,838
CO_2 volume flow CO_2 from biogas/bio-waste	Nm³/h CO_2	9,314	9,314	7,917
CO_2 content	%	99	99	99
Specific energy demand *	kJel, th/kgCO_{2cap}	-	-	-

Large-scale CO_2 capture

Both CO_2 capture technologies presented here are state of the art and have been used on a large scale for decades. Leaps in development are hardly to be expected (Koytsoumpa 2015, Urech 2013 and Schäffer 2013). Values in real operation, however, can deviate significantly from the values given, as these are strongly dependent on the respective framework conditions, e.g., Desired/required CO_2 purity, mass flows, available investment capital, etc:

Amine scrubbing in power plant waste gas:

Technical parameters	Unit	2015	2030	2050	range
Operating hours	h/a	8,410	8,410	8,410	
CO_2 purity	%	98	98	98	95-99
Print Regenerator	bar	2	2	2	1-3
Specific energy demand	kJel/kgCO_{2cap}	40	40	40	
Special heat requirement	MJth/kgCO_{2cap}	3.8	3.8	3.8	3.5-4.2

Selexol® wash in cement flue gas:

Technical parameters	Unit	2015	2030	2050	range
Operating hours	h/a	8,410	8,410	8,410	
CO_2 purity	%	98	98	98	95-99
Print Regenerator	Bar	18|2|0.3	18|2|0.3	18|2|0.3	
Specific energy demand	kJel/kgCO_{2cap}	1100	1100	1100	1100-2200
Special heat requirement	MJth/kg$CO_{2\ cap}$	0	0	0	

Direct air capture

For the following technological and economic parameters, the Climeworks equipment was considered (adsorption) (Climeworks 2018). A complete list of the technological parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Capture capacity	tCO_2/a/module	49	49	49
Temperature level (lower limit)	°C	80	80	80
Temperature level (upper limit)	°C	120	120	120
Lifetime	a	12	12	12
Degradation (per absorption-desorption cycle)	%	0.02	0.02	0.02
Operating pressure	bar	1.01	1.01	1.01
Energy input heat (100 °C)	GJ/tCO_2	7.92	6.57	5.76
Energy use electricity	GJ/tCO_2	2.52	1.85	1.44

The probable improvement in performance data for this technology cannot be quantified reliably.

Components

The reference plant for CO_2 capture from biogas with DWA consists of

- Coarse and fine desulphurisation (depending on H_2S content)
- compressor, drying by gas cooling
- Pressure swing adsorption (4 units with carbon molecular sieve), vacuum pump

The reference plant CO_2 capture from biogas with amine scrubbing consists of

- Coarse and fine desulphurisation (depending on H_2S content)
- Scrubber
- Compressor, gas drying

The amine scrubber for large-scale CO_2 capture consists of

- Scrubbing column at atmospheric/ slightly elevated pressure (1 - 3 bar)
- Expansion drum
- Heat exchanger
- Regeneration Column
- Boilers
- Compressors

The Selexol® scrubber consists of:

- Scrubbing column at elevated pressure (20 - 30 bar)
- Expansion drum(s) at lower pressure stage (0.2 - 20 bar)
- Compressors

The CO_2 separator from Climeworks consists of

- Blower
- Heat exchanger

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2.2.4 Water treatment

Water treatment - surface water and ground water

Module 46: Pre-treatment + membrane (RO)

Module 47: Pre-treatment + ion exchange

Module 48: Combined treatment

Technology description

This fact sheet describes the preparation of surface or ground water to produce hydrogen electrolytically. The three methods of water electrolysis considered in this project - alkaline electrolysis, PEM electrolysis and high temperature electrolysis - have a particular need for water quality (Ursua 2012). The alkaline electrolysis requires high electrolyte concentration. Thus, modern plants use a 25-30 wt.% KOH solution. PEM electrolysers are operated with demineralised water, which has a very high resistivity (>1MΩ*cm; DI water grade 2 according to ISO 3696) (Ursua 2012; Hydrogenics 2017). According to these product parameters, the composition of the ground and surface water must be changed quite considerably depending on the initial quality. First of all, drinking water quality must be achieved through several process steps during the pre-treatment. The pure drinking water is then used as a starting material in other technologies to produce high-purity water.

Surface water must be cleaned of solids and suspended solids by filtration or sieving processes (drum filters or belt screens), followed by flocculation and sedimentation of the small non-filterable particles. A high degree of hardness may require the use of acids (e.g., hydrochloric acid for ion exchange or sulphuric acid) and alkalis (lye precipitation) (Dey 2007; Garfí 2016; Zijp 2015).

Pre-treatment of groundwater is usually less costly, as it often does not require the removal of solids and suspended matter. On the other hand, dissolved iron and manganese often have to be converted by oxidation into iron and manganese oxide hydrates and these have to be filtered out of the water. In this process, sludge is produced as residues from filter backwashing, which must be treated and disposed of.

The demineralised water is obtained by ion exchange from the pre-purified water (Lenntech 2017).

In addition, demineralised water can also be achieved by reverse osmosis (RO) to achieve the high resistance for PEM electrolysers [ewt-wasser 2017]. An essential difference between ion exchange and RO is that no additional chemicals are used for RO, which go beyond the conditioning of the input water. It is also possible to combine both methods to minimise the load on the ion exchange resin.

The modules differ in the treatment methods up to drinking water quality. All variants have an upstream removal of solid impurities. Conventional treatment then includes the following process steps: iron removal, chemical softening, filtration and ion exchange. During the combined treatment, membrane filters and ion exchange resin are used [Zijp / van der Laan, 2015]. The pre-treatment is followed by complete demineralisation.

Technical development trends and development goals

Technical developments in production processes aim at closing the water cycle by regenerating the used water to achieve independence from external water sources. Furthermore, cost reduction is a central issue [DECHEMA, 2016]. In the case of electrolysis, of course, recovery is not possible. This makes the development of economically operated decentralised plants even more important.

Current importance and outlook for 2030/2050

The demand for electricity-based hydrogen - and thus for treated water for electrolysis - will rise sharply in the future, both for PtX energy carriers and for chemical conversion processes such as Ammonia production. In addition, the growing production of epoxy resins is a major driver.

Technological parameters

The following technologies are considered:

- Conventional pre-treatment + membrane (RO)
- Conventional pre-treatment + ion exchange

- Combined treatment

Technical parameters	Unit	2015	2030	2050
Recovery rate (membrane)	%	80	80	80
Power consumption (a)	kWh/m^3	2.9	1.9	0.9
Power consumption (b)	kWh/m^3	0.7	0.6	0.5
Power consumption (c)	kWh/m^3	3.3	2.3	1.3

Components

The following components are included:

- Water collection
- Water pre-treatment
- Desalination process (ion exchange / membrane)
- Sewage disposal

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Module 49: Seawater desalination

Technology description

Large regions are affected by water scarcity, primarily in the Middle East and North Africa, but also in Australia and India, for example. This also limits the availability of water for electrolysis. Desalination of seawater is one possible measure to alleviate this problem (MENAWATER 2011). Most seawater desalination plants today are located in the Middle East in the Gulf States and are based on MSF (Multi-Stage Flash) technology. This is a thermal process in which the raw water is fed to a series of stages at continuously lower pressure. In each stage, the brine boils spontaneously until it reaches its saturation temperature. In each stage, a quantity of distillate (steam) is thus generated (WABAG 2017). The process is very energy-intensive. An improved variant with lower brine temperature is offered by MED (Multi-Effect Distillation) (Gebel 2008, El-Dessouky 2002).

In contrast, RO (reverse osmosis) is a membrane-based process in which the raw water is pumped at high pressure (up to 80 bar) against a selective membrane. The membrane can separate between 94% and 98% of the dissolved salts (Wilf 2007). The typical energy consumption of new RO plants is much lower than that of thermal desalination processes. Therefore RO has experienced enormous growth in recent years. In 2014 about 66% of the globally installed desalination capacity was RO. This was followed by MSF with 23% and MED with 8% (IRENA 2015).

Technical development trends and development goals

Until the end of the last century, thermal desalination processes - especially MSF - had played a dominant role in the desalination market. In the last decades, the selectivity of the membranes could be considerably increased in RO. In addition, for about 10-15 years now, RO systems have been introduced which can further reduce the already relatively low energy consumption. These systems are known as ERD (Energy Recovery Devices). This allows a large part of the pressure energy that is still present in the brine to be released back into the raw water (Pressure Exchange Systems). In the case of thermal desalination processes, it is being investigated whether an alternative choice of materials can be advantageous for the evaporators. In the case of RO, current research focuses on the additional improvement of the selectivity of the membranes, the design of both the membrane arrangement and the entire plant (Penate 2012). The supply of renewable energies will also play an increasingly important role.

Current importance and outlook for 2030/2050

In 2015, the total globally installed desalination capacity was about 87 million m^3/day. More than 300 million people worldwide are currently dependent on desalination (IDADESAL 2017). According to IRENA 2015, the annual growth in installed desalination capacity worldwide is 9%. According to (DESALDATA 2017) new desalination plants with a total capacity of about 10 million m^3/day are installed every year. Of this, about 90% are RO plants. Until 2030 an annual increase in installed desalination capacity of approx. 15 - 20 million m^3/day is predicted (DESALDATA 2017).

Technological parameters

In the current project only reverse osmosis (RO) for seawater is considered:

Technical parameters	Unit	2015	2030	2050
Recovery rate	%	35-45	40-50	45-55
Power consumption	kWh/m³	2.2 – 2.5	2.2 – 2.5	2.0
Selectivity membranes	%	94 - 98	96 - 99	98 - 99
Operating pressure	bar	55 - 75	55 - 75	55 - 75
Lifetime	a	25	25	25
Availability	%	92	94	95

Components

- Water inlet
- Water pretreatment
- Desalination process
- Post-treatment of drinking water
- Brine disposal

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2.2.5 Transport of electricity and energy carriers

To be able to evaluate the supply of synthetic energy carriers in Germany, long-distance transport must also be taken into account. This is particularly relevant if the production takes place outside Germany. There are basically two options:

1. Transport of electricity to Germany and production on site; or
2. Generation of the energy carriers abroad with subsequent transport to Germany.

High voltage direct current transmission lines are considered for the transport of electricity, while liquid energy carriers can be transported by ship and truck. Gas transport is also possible via liquefied gas tankers and pipelines. For the technology profiles the results of the UFOPLAN project "Klimaschutz und regenerativ erzeugte chemische Energieträger –Infrastruktur und Systemanpassung zur Versorgung mit regenerativen chemischen Energieträgern aus in- und ausländischen regenerativen Energien" were evaluated. In addition, investigations on specific costs and losses of different options for long-range hydrogen transport and HVDC power lines and corridors[10], as available at DLR, were used.

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Module 50: Power transmission with high-voltage direct current (HVDC) transmission

Technology description

Electricity transmission and distribution grids, including substations and switching stations, provide the link between generation and consumption, with overhead lines and cables being the main connecting elements. In contrast to the alternating current (AC) overhead lines which dominate today, high-voltage direct current (DC) transmission lines are considered for the development of the transmission network.

High voltage direct current (HVDC) transmission technology is mainly used to transmit high power over long distances. The energy can be transported in both directions. Overhead lines or underground cables can be used overland. HVDC transmission lines are currently still almost exclusively implemented as point-to-point connections, whereby underground cables are sometimes designed monopolar with the earth as return conductor and overhead lines as bipolar circuits. The latter promises a higher security of supply in the event of a fault. If a line of a bipolar route fails, half of the transmission power is still available. A networked system comparable to the alternating current system enables the multi-terminal technology, which is, however, much more complex to control and implement. The first multi-terminal plant built by ABB is located in Quebec (ABB 2008).

Another application of HVDC is electrical submarine cable connections. The structure and materials used for conductors/conducting layers, insulation, padding and armouring differ from overhead lines and underground cables. As a rule, underground and submarine cables have an internal copper conductor. Due to the high losses of AC cables, cable-based connections from about 80 km are only possible with HVDC transmission (Siemens 2012). A mixed use of cables and overhead lines or sea and land cables is also possible.

Advantages and disadvantages of the different technologies:

DC overhead lines have much lower power losses than AC extra-high voltage overhead lines - in the range of 4-5%/1000 km due to the lower heat generation in the conductor. They cause significantly lower electromagnetic radiation and, due to the higher transmission power, less land use than AC lines (May 2005, Hess 2013). As a rule, 30-40% more energy transmission is possible with HVDC transmission at the same route width than with conventional AC overhead lines (Siemens 2012). The higher the voltage, the lower the transport losses and the more energy can be transmitted via the line (Siemens 2012). Due to the costs and losses of the converter stations, however, HVDC transmission lines are only more economical than AC lines from a length of about 600 km upwards (Siemens 2012).

The use of underground cables causes much higher costs (approx. factor 5-8 higher than overhead lines), but promises a much higher acceptance among the population for the network expansion. Soil management above the underground cables is possible, but there should be no deep-rooted plants and no overbuilding in the cable protection strip. HVDC transmission is also advantageous for long underground cable routes, as reactive power compensation is necessary for AC cables of approx. 100 km in length or more.

Technical development trends and development goals

In the case of DC connections, research and development is aimed at reducing transmission losses by raising the voltage, the technical realisation of networked HVDC transmission lines and the expansion of the power range of line-commutated HVDC transmission lines, which are characterised by significant advantages in terms of flexibility in reactive power control compared with conventional technology. For economic reasons, the technology design and the choice of the required transmission voltage depend on the power to be transmitted. The technological parameters and costs for a 600 kV HVDC transmission system in point-to-point (bipolar) design are shown below as examples. In the DC systems, between 1997 (1st Generation with a two-point converter) and 2010 (4th generation, HVDC transmission light with cascaded two-point converters), the converter losses were reduced from 3% to approx. 1%, while the switching frequency was minimised (ABB 2011).

Basically, two technologies can be distinguished today for the transformation of three-phase current into direct voltage, which can be classified as grid-commutated and self-commutated operation (ABB 2014). Conventional facilities are available today with a capacity of up to 6000 MW per transmission at a DC voltage of up to ± 800 kV.

In the future, an increasing transmission power at higher voltage can be expected. The multi-terminal technology required for cross-connections is not yet economically feasible.

In the case of DC underground cables, developments to further reduce costs while simultaneously increasing transmission performance are essential to increase the application potential. The implemented state of the art is 1800 A and 320 kV, corresponding to about 1 GW transmission power for a bipolar line (Hess 2013). The state of the art for DC submarine cables is 1.6 GW transmission capacity (1,600 A at 500 kV), and the installation depths are specified up to about 1,500 m below sea level (Hess 2013). More recent developments of 525 kV and 640 kV extruded HVDC transmission cables promise much higher transmission capacities of over 2 and over 3 GW for future lines (NKT 2018, ABB 2016). ABB's development objectives were also stated with regard to VSC HVDC transmission with a DC voltage of ± 640 kV, a transmission capacity of 2.4 GW and losses per converter of < 0.9% (ABB 2011). For DC submarine cables, voltages of ± 640 kV and water depths of up to 2,000 m are also the goal of future implementations. In addition, further research is being conducted on electronic and mechanical DC circuit breakers and the design of DC grids (e.g., OffshoreGrid).

The stability of the power supply in case of disturbances places high demands on the new HVDC transmission technologies. New control strategies are required for power control in mains DC networks, primary control (definition "reference variable") and the influence of mass inertia. In addition, work on the normalisation of HVDC transmission technology and control must be completed.

Current importance and outlook for 2030/2050

At the turn of the millennium, approx. 60 GW of transmission capacity was already installed worldwide using HVDC transmission technology. By 2012, HVDC transmission links with a total of 100 GW had been implemented. It is expected that this number will have tripled in the next few years (Siemens 2012). The number of projects realised in 2012 was in the region of 140 (ABB 2011). Distances of up to several 1000 kilometres are bridged. HVDC transmission is therefore a mature technology.

According to the company, Siemens commissioned the world's first 800 kV HVDC transmission system in China at the end of 2009. With the "Western Link" between Scotland and England, Siemens is installing the world's first submarine cable HVDC transmission link with 600 kV and 2.2 GW transmission capacity (Siemens 2012).

The global market for electricity transmission (including HVDC) is expected to continue to grow in the coming years. Today it is expected to be in the order of €5 to 9 billion per year. The market for HVDC transmission has developed strongly in recent years.

Technological parameters

Below is a list of the respective components and corresponding technical parameters of an HVDC technology with long-term transmission power of over 3 GW and ±600 kV transmission voltage as parameter data for the project. (DLR/ISE/IFHT 2012)

HVDC - bipolar	**Unit**	**2015**	**2030**	**2050**
System type		simple	simple	simple
Voltage	kV	600	600	600
Limit power per circuit 2050	MW	3,200	3,200	3,200
Transmission losses of overhead line per 1000 km	%	4.5	4.5	4.5
Conduction losses underground cable per 1000 km	%	3.4	3.4	3.4
Conduction losses submarine cable per 1000 km	%	2.6	2.6	2.6
Station losses per station	%	0.7	0.7	0.7

Components
The HVDC technology for long-distance power transmission consists of the following components: - AC/DC converter stations (2 per point-to-point connection) - Overland line (bipolar) - Earth cable (bipolar) - Submarine cable (bipolar)

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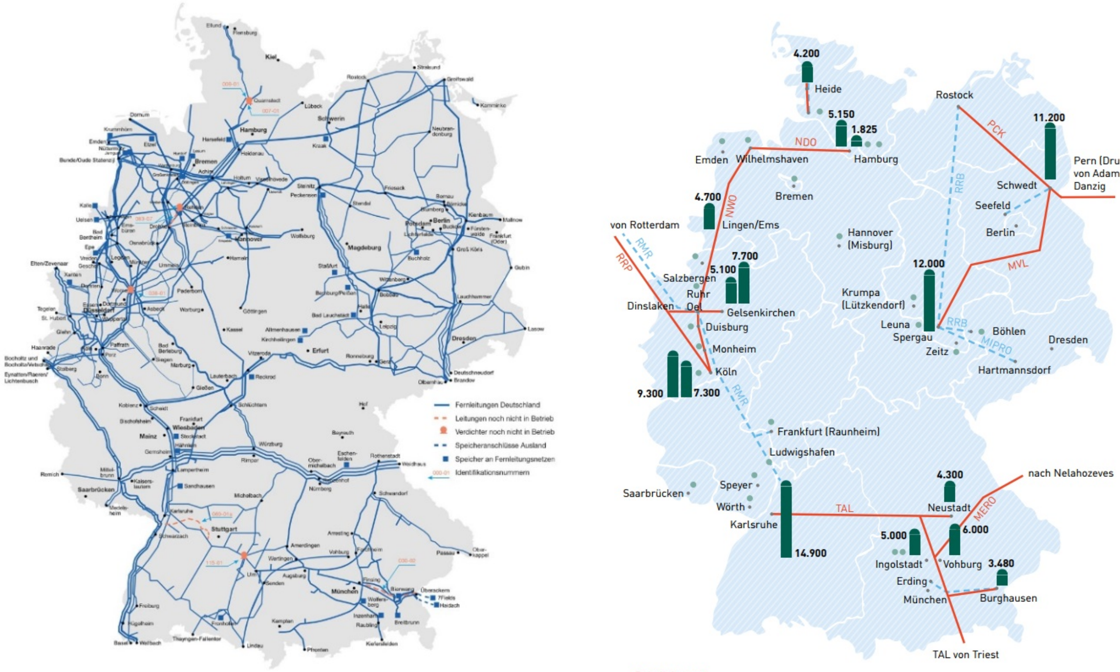
Module 51: Transport - Pipeline

Technology description

Gases and liquids can be transported by pipeline. For some of the PtX energy carriers - FT crude oil and products, synthetic natural gas and, to a limited extent, hydrogen the existing pipeline infrastructure in Germany and Europe could be used. Methanol, on the one hand, is so corrosive that it may be necessary to build up a separate pipeline infrastructure. Liquid energy carriers can also be efficiently transported by tankers and trucks due to their higher energy density. This can also be seen in a comparison of the current gas and oil infrastructure in Germany.

Figure 18: Overview of gas and oil pipelines in Germany



Source: Transmission system operator

The demand for crude oil in Germany in 2017, excluding secondary access, was about 3,890 PJ. Around 2.4% of this was produced domestically. About 80% of imports are via oil pipelines from Rotterdam, Trieste and Russia. A total of 9 companies operate 14 import crude oil pipelines in Germany or with connections abroad (status at the end of 2016). Their total length in Germany is about 2,000 km with a maximum annual transport capacity of up to about 200 million t ROE. Some of the pipelines are also used in both directions and some of the oil is also transported to other countries. (MWV 2017b, 50f.) In addition, there are 6 pipelines that transport petroleum products to interim storage facilities or for further processing.

In 2016, the German gas pipeline network will have a total length of approx. 479,000 km, of which 158,500 km will be low-pressure, 200,500 km medium-pressure and 120,000 km high-pressure. The transmission network is maintained by 16 operators, who also operate 72 compressor stations in addition to the grid. Furthermore, there are 49 underground gas storage facilities at 39 locations in Germany. These can hold a capacity of 24 billion m^3 working gas and have a maximum withdrawal capacity of 676 million m^3/day. This means that gas storage facilities can provide about a quarter of the natural gas volume consumed in 2016. The development of the infrastructure in Germany is not only dependent on its own supply requirements. Due to its geographical location and the presence of large natural gas storage facilities, Germany has a distribution function (gas hub) for Europe. With a volume of 4,778 PJ of imported natural gas, 973 PJ of natural gas were exported in 2017 (Horst 2018).

Natural gas pipelines also run from North Africa (Algeria and Libya) across the Mediterranean to Spain and Italy. However, the European transmission network is not fully developed for transit in both directions.

There are two main aspects that are important for the LCA in this project:

- Energy expenditure and (methane) losses during pipeline operation
- Cost of materials and environmental impact of pipeline construction

During transport, gas and liquid products lose energy through friction on the walls of the pipeline. Compressor or pumping stations therefore have to rebuild the pressure at regular intervals. In the natural gas grid, these compressors are operated directly with natural gas from the pipeline, but sometimes also electrically. In addition, leaks occur at the stations, which result in the direct escape of methane.

The energy and methane losses of today's pipelines are stored in the ecoinvent life cycle assessment database. (Wernet 2016) and serve as a conservative estimate of the current situation. The study (DBI 2016), which specifically examined transport in Germany, the Netherlands, Norway and Russia, comes to somewhat more favourable results. These data are adopted for the reference year 2030, as a continuous retrofitting and improvement of the infrastructure is expected. The life cycle assessment for the Nord Stream 2 pipeline (Russ 2017), which is currently under construction, serves as a best case scenario for the values in 2050.

Unlike synthetic natural gas and bio natural gas, hydrogen differs greatly in its gas composition from conventional fossil natural gas. In principle, it is possible to add hydrogen to the base gas as long as the limits of the base gas composition are met and the hydrogen tolerance of the customers, the gas infrastructure and its components are not exceeded. In general, it can be assumed that the existing natural gas infrastructure is largely suitable for approx. 10 vol% H_2 in natural gas. Gas application equipment is still being tested today with different gas qualities, including natural gas containing 12 vol.% H_2.

Technical development trends and development goals

By improving the energy efficiency of the compressor stations and reducing flow resistances in the pipeline, it should be possible to reduce the energy consumption of the gas transport pipelines by up to 20%[Liu et al., 2014]. This is taken into account in the figures for the year 2050.

Current importance and outlook for 2030/2050

To estimate whether the German gas and oil network is sufficient to transport future PtX energy carriers in the face of declining natural gas and oil imports (Horst 2018), the quantities of PtX substances are compared (Horst 2018) in several future scenarios, including the UBA study THGND (UBA 2014). The scenarios show that the total demand for fuels will decline over the years due to efficiency measures in buildings and processes as well as an increasingly electricity-oriented energy supply. In the medium to long term, existing infrastructures will no longer be able to meet the declining demand for fuels and combustibles. For grid-bound infrastructures such as pipelines in particular, the question arises as to whether dismantling is technically necessary.

Technological parameters

Data for energy and methane losses in pipeline transport of gas and oil to (Wernet 2016; DBI 2016; Russ 2017). A complete list of technology parameters can be found on the website of the Federal Environment Agency.

Technical parameters	Unit	2015	2030	2050
Gas pipeline (gas)	MJ/tkm	1.0	0.95	0.75
Gas pipeline: Methane loss	%/1000 km	0.13	0.10	0.040
Oil pipeline, offshore - (diesel)	MJ/tkm	0.45	0.45	0.45
Oil pipeline, onshore - (electricity)	MJ/tkm	0.072	0.072	0.072

Components

The following components will be considered:

- Infrastructure (pipelines, compressor stations, pumping stations)
- Transport pipeline energy consumption (electricity, natural gas, oil or PtL or PtG)
- Direct emissions (from own consumption of pumps, compressors)

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Module 52: Transport - Ship

Technology description

Worldwide, maritime transport has grown steadily over the past decades. It is expected to grow by 2 to 3% per year until 2020. Shipping is already responsible for over 2% of global CO_2 emissions in the world's oceans. In 2012, these emissions will amount to approximately 940 million tonnes of CO_2.

Of particular interest for this project are the emissions from large tankers (Panamax, Suezmax) which can transport liquid or liquefied PtX energy carriers to Germany. Today they are still driven by diesel engines - mainly with heavy fuel oil (HFO), in coastal sulphur control areas (SECA) also with higher quality low sulphur marine diesel oil (MDO).

Technical development trends and development goals

In 2008, the International Maritime Organization (IMO) set a reduction in the globally applicable limit for sulphur in marine fuel from the current 3.5% to 0.5% from 2020 (MARPOL Annex VI). The EU has implemented the sulphur content requirements in marine fuel from MARPOL Annex VI with the EU Sulphur Directive (2012/33/EU). This means that in European waters not designated as SECA (e.g., North-East Atlantic, Mediterranean, Black Sea), a maximum sulphur content of 0.5% will be mandatory for all ships regardless of their flag from 2020. This can be achieved using marine diesel oil (MDO), liquefied natural gas (LNG) or through emission control systems. In the context of this project, only the first two options are considered.

Today, LNG propulsion systems are almost exclusively used on tankers that transport liquefied gas themselves. There, the inevitable 'boil-off gas' is available as fuel. However, the wider use of this fuel is being intensively investigated. In addition to steam turbines, which are still frequently used today, LNG/SNG combustion engines, which are more efficient, will also be used in future.

Methanol and hydrogen do not yet play a role as fuels today. Methanol is being researched, at least in pilot projects on smaller ships.

Accumulators or fuel cells are currently only being tested for auxiliary power units or smaller classes of ships on short sea routes.

Current importance and outlook for 2030/2050

For 2015 and 2030, HFOs and MDOs play the dominant role.

Later, many of the PtX energy carriers considered in this project can also be used as marine fuels. From today's perspective, it is not possible to say which of these can be established. On the other hand, it is unlikely that several synthetic energy carriers will be available in large quantities in the time horizon 2050. It therefore seems reasonable to assume that the PtX fuel transported in 2050 will also be used to power ships. This would be either FT diesel, liquefied (bio)methane or methanol.

With regard to the development of efficiency, the more conservative estimate of the IMO path is based on a 40% increase in efficiency between 2012 and 2050 (Smith 2015). However, very little data is currently available for methanol.

Technological parameters

The energy consumption for transport by ship is calculated for the respective location with EcoTransITWorld. (Ecotransit 2017). For the years 2030 and 2050, efficiency increases of 8.5% and 37% respectively compared to 2015 are assumed (Smith 2015).

The emission factors for onboard combustion (Tank-to-Propeller, TTP) are based on Brynolf 2014.

The following table gives an example of the values for voyages of a tanker of the Suezmax class (120-200,000 dwt) between Casablanca, Morocco to Rotterdam, Netherlands. The loading rate is 48% due to the unavoidable empty runs.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Energy demand	MJ/tkm	0.088	0.081	0.055
Emission factors TTP				
		HFO (heavy oil, 1% sulphur)	HFO (heavy oil, 1% sulphur)	FT-Diesel
CO_2	g/MJ fuel	77	77	73
CH_4	g/MJ fuel	0.00045	0.00045	0.00045
NO_x	g/MJ fuel	1.6	1.6	0.28
SO_2	g/MJ fuel	0.69	0.69	0.000091
PM10	g/MJ fuel	0.093	0.093	0.011
		MGO (Marine Gas Oil, 0.1% sulphur)	MGO (Marine Gas Oil, 0.1% sulphur)	LSNG (liquefied synthetic natural gas)
CO_2	g/MJ fuel	73	73	54
CH_4	g/MJ fuel	0.00045	0.00045	0.63
NO_x	g/MJ fuel	0.28	0.28	0.11
SO_2	g/MJ fuel	0.047	0.047	0
PM10	g/MJ fuel	0.011	0.011	0.0043
				Methanol
CO_2	g/MJ fuel			69
CH_4	g/MJ fuel			0
NO_x	g/MJ fuel			0.28
SO_2	g/MJ fuel			0
PM10	g/MJ fuel			0.0043

Components

The following components are included:

- Ship (depreciation over lifetime and annual transport performance)
- Direct emissions from ship propulsion
- Leaks (methane slip)

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Module 53: Transport - Truck

Technology description

Truck transport within the project refers on the one hand to large tanker trucks (26-40 t gross vehicle weight (GVW), which deliver liquid energy carriers such as synthetic diesel, methanol, etc. from the place of production or port of landing to the final destination (centre of Germany). In addition, the transport of biomass with medium-heavy trucks (7.5 - 12 t gross vehicle weight) can also be mapped with this module.

The diesel engine is today the most widely used and cost-effective drive system for heavy-duty commercial vehicles. Due to the high energy density of diesel fuel, very long ranges are possible. Today's trucks of this size class need about 0.9 MJ diesel to transport one tonne of goods one kilometre - including the average empty runs. This value is significantly higher than for rail transport (approx. 0.3 MJ/tkm) [ifeu 2014].

Technical development trends and development goals

Potentials for increasing the energy efficiency of diesel trucks are discussed in (ifeu/TU Graz 2015 and TU Wien 2011). These include downsizing, downspeeding, recuperation/boost, electrification of auxiliary consumers, GPS based EMM, waste heat recovery and reduction of driving resistances.

For heavy commercial vehicles, there are no legal regulations to date to reduce specific fuel consumption. Therefore, analogous to the trend scenario described in (UBA 2016), a reduction of 8% on average is assumed, i.e., a total reduction of around 20% by 2030. The reduction of diesel trucks differs according to size class until 2030:

- Trucks up to 12t permissible TW: -23%.
- HGVs over 12t permissible TW: -21%.
- Trucks and articulated lorries: -19

The extrapolation up to 2050 for internal combustion vehicles is also based on the results of (UBA 2016).

Current importance and outlook for 2030/2050

For the time horizon until 2050, the following technological options are available for low GHG long-distance road freight transport:

- diesel trucks running on PtL fuels,
- CNG/LNG operated with PtG fuels or trucks designed as dual-fuel vehicles,
- fuel cell electric trucks running on PtG hydrogen
- Electricity/PtL powered hybrid overhead line trucks

CNG/LNG trucks are already in use today, mainly in the USA and China. The advantage of LNG over CNG is its higher energy density, so that a greater range can be achieved with smaller tank volumes. In contrast to diesel engines, the petrol engines required for the combustion of the gas have a slightly lower efficiency. Whether the RE requirement in the overall energy system is lower than when using PtL in the diesel engine therefore depends in particular on the reduction of the additional consumption of the gas engine or on the use of dual-fuel technology.

Long distance trucks are discussed with both compressed and liquefied **hydrogen.** Fuel cell trucks currently exist only in the form of prototypes. Although the energy density of the stored hydrogen, especially in liquid form, allows a sufficient range for use in long-distance trucks, challenges lie in the cost, the use of rare materials and the durability of the fuel cells. Compared to internal combustion engine concepts, the key factors are higher efficiency and the avoidance of direct emissions. The main difference between the transformation path and combustion engine concepts is that conversion cannot start from existing fossil fuels. A separate infrastructure for hydrogen-powered vehicles must be established.

The use of **overhead contact line systems** for direct supply of vehicles with high energy demand, without the need for batteries, is a technology that has been tried and tested in urban bus traffic. This technology could be transferred to trucks in long-distance transport. The focus is on the motorway performance of heavy long-distance commercial vehicles, in particular articulated lorries. This requires the installation of overhead contact lines on the infrastructure side, at least on motorway chapters that are particularly heavily used by the user group, and pantographs (current collectors) on the vehicle side. In line with the discussion in ENUBA (Siemens/TU Dresden 2016) and the German government's mobility and fuel strategy (MKS 2013), the vehicles are to be designed as diesel/electric hybrid overhead line vehicles (OHVs). Like fuel cell trucks, OHVs are currently in the development and research phase.

The main obstacle to the introduction of the OHV is the development of the infrastructure, since only when the (European) motorway network has a high coverage is there flexibility of use for the hauliers. (UBA 2016)

Technological parameters

This study does not focus on the evaluation of drive technologies. Therefore, a plausible pre-selection must be made.

For the situation today, medium and heavy conventional diesel trucks are assumed, and individual transport journeys are calculated with EcoTransIT World (ifeu 2014). Typical loading levels and empty runs are taken into account.

For the situation in 2030, electrically powered vehicles for medium-heavy trucks (<12 t) and for heavy trucks (up to 40 t) will also be introduced for overhead line hybrid vehicles. For 2050, LNG propulsion will be added for heavy trucks. Progress in efficiency will be assessed in accordance with (UBA 2016) or additional internal calculations.

Technical parameters	**Unit**	**2015**	**2030**	**2050**
Solo trucks up to 12t (average goods) Fuel consumption				
Diesel	MJ/tkm	3.7	3.3	2.4
Electricity	MJ/tkm		1.9	1.7
Capacity utilisation (including empty runs)	%	34	35	37
SNF up to 40t (for bulk goods) Fuel consumption				
Diesel	MJ/tkm	0.74	0.66	0.50
Electricity	MJ/tkm			0.32
LNG	MJ/tkm			0.70
Capacity utilisation (including empty runs)	%	63	64	69

Components

The following components are included:

- Truck production (vehicle, combustion engine, Li-Ion battery)
- Overhead line construction
- Direct emissions from internal combustion engines

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3 Excursus: Alternative hydrogen processes

In this chapter, the prospects for the production and supply of renewable hydrogen by processes still in their infancy are presented - in addition to the already established technologies available on an industrial scale. The following hydrogen production processes were considered:

- photocatalytic water splitting,
- photoelectrochemical water splitting and
- thermal water splitting with thermochemical cycle processes.

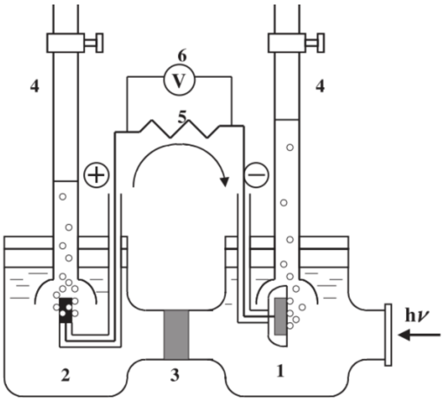
For the processes, a detailed description of the state of research and development and important technical parameters (such as energy input per fuel unit, efficiencies of the process steps, requirements on raw materials, product quality) were presented as far as possible on the basis of literature research. In addition, an assessment was made of the possible applications of the processes, compatibility with the energy system, flexibility, limits and challenges of further development, as well as possible bottlenecks in large-scale use (e.g., material availability and its substitution). Where already possible, optimisation possibilities such as efficiency increases and cost reductions are also discussed. However, the data situation here is not yet certain so that data cannot be derived for reference plants which have the necessary quality for further LCA consideration.

3.1 Photocatalytic water splitting

In 1972, Honda and Fujishima, two scientists from Japan, succeeded in splitting water photoelectrochemically with light for the first time. The photoelectrochemical cell used for this was equipped with two electrodes. The anode was an n-doped TiO_2 electrode (titanium dioxide) and the cathode was a platinum electrode. Figure 19 shows the cell schematically.

When Honda and Fujishima irradiated the TiO_2 electrode with light in the wavelength range below 415 nm (photon energy >3 eV), an anodic current began to flow, which was proportional to the irradiated light intensity. By the direction of the current flow, the scientists concluded that oxidation (O_2 development) took place at the TiO_2 electrode and reduction (H_2 development) at the platinum electrode.

Figure 19: Schematic representation of a photoelectrochemical cell



1) n-doped TiO_2 electrode; 2) platinum counter electrode; 3) ion conductive membrane; 4) gas burette; 5) load resistance; and 6) voltameter.
Source: Kazuhito, Hiroshi & Akira, 2005

They postulated a photochemical reaction of water splitting according to the following scheme

a) Anode:

1. $TiO_2 + 2\,\hbar\omega \rightarrow 2e^- + 2p^+$
2. $2p+ + H_2O \rightarrow \frac{1}{2}\, O_2 + 2H^+$

b) Cathode:

3. $2e^- + 2H^+ \rightarrow H_2$

c) Overall reaction:

4. $TiO_2 + 2\,\hbar\omega \rightarrow \frac{1}{2}\, O_2 + H_2$

- Equation 1 states that the excitation of TiO_2 by photons ($\hbar\omega$) leads to the formation of an electron(e-)-hole(p+) pair.
- In equation 2, holes initiate the oxidation of the water with the release of oxygen and protons, whereby the electrons migrate to the counter electrode.
- On the cathode side, the electrodes then reduce the protons produced to molecular hydrogen in equation 3 as a counter-reaction to the anode.
- Equation 4 represents the total reaction according to which one mole of water and two moles of photons generate one mole of H_2 and half a mole of O_2 by light.

Mechanistic principles of photocatalytic water splitting

There are two approaches to hydrogen and oxygen generation by photo-induced water splitting:

- By a single step on a photocatalyst (overall), or
- by two coupled steps (coupling of the half reactions) by combining two photocatalysts and the use of redox mediator systems for charge exchange (Z scheme)

3.1.1 The overall water splitting

For this reaction scheme, electrons have to be transported from the fully occupied valence band (VB) of the semiconductor (e.g., TiO_2) into the energetically higher empty conduction band (CB) in the first step. This is done by photons (light), which must have a higher energy than the band gap (energetic distance between VB and CB) of the semiconductor.

This creates the electron-hole pair, which migrates to the surface of the semiconductor and here initiates the oxidation of water, as described in equation 2, and the reduction of protons, as described in equation 3 [Jeffrey R. Bartels 2010].

The mobility and the separation of the electron-hole pair from each other and the prevention of recombination are crucial for the effectiveness of the catalyst. Only if recombination is prevented and the electron-hole pairs diffuse unhindered to the surface of the catalyst, the reactions in equation 1-3 can run efficiently.

To prevent recombination and to keep the diffusion paths of the electron-hole pairs to the surface of the catalyst as short as possible, the semiconductor material properties can be modified with regard to crystallinity and particle size and so-called co-catalysts can be used.

For example, by reducing the particle size, the diffusion path of the electron-hole pairs to the surface of the photocatalyst can be shortened, thereby accelerating their migration to the surface [Maeda 2011]. In addition, by increasing the crystallinity of the semiconductor, the defect sites in the material can be reduced, which also has a positive effect on the migration of the electron-hole pairs to the surface [Xing 2012]. The use of a co-catalyst on the surface of the semiconductor guarantees the provision of the active centres for reduction or oxidation and thereby lowers the activation energy of the chemical reactions. As a result of the faster reaction, the recombination rate of the electron-hole pairs is reduced, thus increasing the photocatalytic activity [Kazuhiko & Kazunari 2007].

Important thermodynamic parameters for the photochemical process of water splitting are the potential limits of the material. The conduction band (CB) must have a

- lower potential more negative than the redox potential of $H+/H_2$ (0 V vs. SHE and pH=0), and
- for the valence band (VB) an upper potential more positive than the redox potential of H_2O/O_2 (1.23 V vs. SHE and pH=0).

Consequently, the thermodynamically required energy to split water is greater than 1.23 eV. This means that under optimal conditions all photons with a wavelength < 1000 nm can induce the splitting of water. Theoretically, therefore, the entire spectrum of visible light (400-800 nm) can be used for the splitting of water. However, due to the inhibited charge transfer between the photocatalyst and the water, greater photon energy is required to excite the electrons in the semiconductor, with the result that visible light cannot efficiently trigger water splitting [Kazuhiko & Kazunari 2007].

This is one of the reasons why only a few photocatalysts have been able to split water in visible light in one step. In addition, other material properties such as the small band gap < 3 eV, the appropriate potentials of the band edges and the stability of the photocatalyst in the reaction make the search for a suitable semiconductor for splitting water in visible light more difficult [Abe 2011, Kazuhiko 2009]. Outside of the laboratory scale, no plant is known to date that pursues this concept.

3.1.2 Photocatalytic water splitting according to the Z scheme

Bard first described in 1979 the photocatalytic water splitting by the combination of two photocatalysts via an electron mediator, the so-called Z-scheme [Bard 1979]. As in the overall process, the same steps of excitation, electron-hole pair formation and migration of these to the catalyst surface also take place in the Z-scheme.

However, it is the generation of hydrogen and oxygen that is specifically targeted on specially implemented catalysts. The electron mediator also determines which reactions take place first. If, for example, sodium iodide is used as a mediator, the water is first reduced by the excited electrons which are located in the CB of the H_2 photo-catalyst. During this process, the iodide mediator is oxidised to iodate and the resulting holes are filled. The oxidised electron mediator is then reduced back to iodide by the excited electrons from the conduction band of the O_2-photocatalyst with simultaneous oxidation of the water.

Compared to overall water splitting, photocatalytic water splitting according to the Z scheme offers the great advantage of more efficient use of visible light, since less energy is needed to excite both photocatalysts [Kazuhiko 2013]. The thermodynamic prerequisites are now derived from this:

- The potential limit of the CB must be a more negative potential than the redox potential of H^+/H_2 (0 V vs. SHE and pH=0), or
- an O_2 photocatalyst in which the upper limit of VBs has a more positive potential than the redox potential of H_2O/O_2 (1.23 V vs. SHE and pH=0)

Since, in contrast to the overall concept in the Z-scheme concept, a photocatalyst no longer has to fulfil both conditions at the same time, a wider range of semiconductors fulfils the necessary conditions. In addition, the Z-scheme has an industrial application due to a locally separated generation of the gases and thus the possibility of tapping pure gases, which has not been the case with the overall concept (gas mixing in the reaction chamber) so far.

3.1.3 Photocatalysts for photochemical water splitting

The required voltages and losses and thus the efficiency of photocatalytic water splitting is, as described, a characteristic property of the selected photocatalysts, which consist either of a homogeneous catalyst complex or of heterogeneous semiconductors. So far, there are only a few heterogeneous systems that are capable of achieving total water splitting with a single photocatalyst or with two photocatalysts [Maeda 2011, Kudo & Misekia 2009]. In recent years, inorganic semiconductors in the range of UV and visible light - such as metal oxides, metal nitrides, sulphides, oxynitrides and oxysulphides [Schröder 2015] - have mostly been used. Metal-free, polymeric, graphitic carbon nitrides have also recently been successfully used as organic semiconductors to develop H_2 and O_2 with visible light [Wang 2009]. While the large polymeric carbon nitrides have a low potential for hydrogen development, it has been shown that changes in the chemical or nanostructure of the materials can increase the photocatalytic efficiency. For example, porous surface structures could be created by "hard templating", which dramatically increased the catalytic performance of the carbon nitrides [Kazuhiko 2009, Wang 2009]. However, it is generally difficult to compare research results in the field of photocatalytic water splitting, since the photocatalytic efficiency of many catalysts for H_2 or O_2 development is influenced by completely different conditions or test reactors. Up to now, photocatalytic water splitting has not yet reached a level that can be used on a large scale. The work on photocatalytic hydrogen production relates exclusively to catalysts in laboratory systems. However, a scale up of these systems has only been published once in the course of the project "Light2Hydrogen- L2H" [Schwarze 2014].

3.2 Photoelectrolytic water splitting

As already described under photocatalytic water splitting, electron-hole pairs must also be generated in the case of photoelectrochemical water splitting to initiate water splitting.

Process description

The process can be combined for a photoanode based system:

- A photon with greater energy than the band gap hits the anode and creates an electron-hole pair, so that a voltage difference is created between the two differently doped semiconductor regions.
- The "holes" decompose the water on the surface of the anode and form protons and gaseous oxygen, while the electrons flow back through the back of the anode, which is electrically connected to the cathode.
- The protons migrate through the electrolyte to the cathode to react with the electrons and form hydrogen
- The separation of oxygen and hydrogen gases is achieved by using semi-permeable membranes.

However, in this case, charge separation (electrons and holes) is achieved by applying a potential gradient at the location of the primary photoexcitation. Such a potential gradient can be created by connecting the semiconductor to a second electrode at the interface between a semiconductor and an electrolyte. The electrons formed at the semiconductor electrode by irradiation can be conducted to the counter-electrode via an external circuit.

In addition to the chemical (redox) reaction (water and oxygen production) on the surface of the two electrodes, a simultaneous flow of electrons from the anode to the cathode is created, which can be used by a consumer [Kaneko & Okura 2003].

In the case of the photoelectrochemical cell presented by Honda and Fujishima (Figure 19), a titanium dioxide semiconductor electrode and a platinum counter electrode were used. A proton conductive membrane was used to separate the electrolyte compartments. This separation of the reaction spaces also made it possible to separate the products hydrogen and oxygen - quite in contrast to the photocatalytic reaction according to the overall concept. Since oxygen and hydrogen are produced spatially separated from each other, there is no need for a later, complex separation.

If the photoanode consists of a semiconductor, which catalyses only one of the two partial reactions of water splitting due to its band structure, water splitting can additionally be initiated by an externally applied voltage [Chen 2012]. Although in this case one is still dependent on an external power source, a lower voltage is required for water splitting than in a regular electrolysis without photoanode.

3.2.1 Photocatalysts for photoelectrochemical water splitting

Numerous materials have already been investigated for use in photoelectrodes, such as Thin film WO_3, Fe_2O_3 and TiO_2 as well as n-GaAs, n-GaN, CdS and ZnS for the photoanode and CIGS /

Pt, p-InP / Pt and p-SiC / Pt for the photocathodes [Akikusa & Khan 2002, Mor 2006] In order to maximise the efficiency of the photoelectrochemical process, the energetics of the electrochemical reaction must be harmonised with the solar radiation spectrum, i.e., a broadband use of the radiation must be enabled. This poses a non-trivial problem. A material with poor adaptation to the solar spectrum can lead to the creation of photo-induced holes, which either cause surface oxidation and thus the formation of a barrier layer on the semiconductor surface, or corrosion of the electrode by dissolution [Norbeck 1996]. The two critical parameters of photoelectrochemical materials are lifetime and quantum efficiency, both of which have so far been considered insufficient. A lifetime of several thousand hours, as would be necessary for a large-scale technical application, has not yet been achieved. Similarly, the quantum efficiency is far below that of solar cells. The simplified design compared to a system of solar cells and classical electrolysis has not yet been able to compensate for the disadvantage of lower efficiency and shorter life span.

3.3 Outlook photocatalytic and photoelectrocatalytic water splitting

Unfortunately, both of the technologies described above are currently still far from commercial application despite the large number of photocatalysts developed. According to model calculations, the efficiency of converting solar energy to hydrogen would have to be around 10% for this type of energy conversion to be economically viable [Tacca 2012]. This is especially true in the visible light range. For wide ranges of the solar spectrum, no catalyst system has yet been developed that could fulfil this condition. A better understanding of the relationships and processes involved in photocatalytic water splitting on semiconductor catalyst systems with regard to their

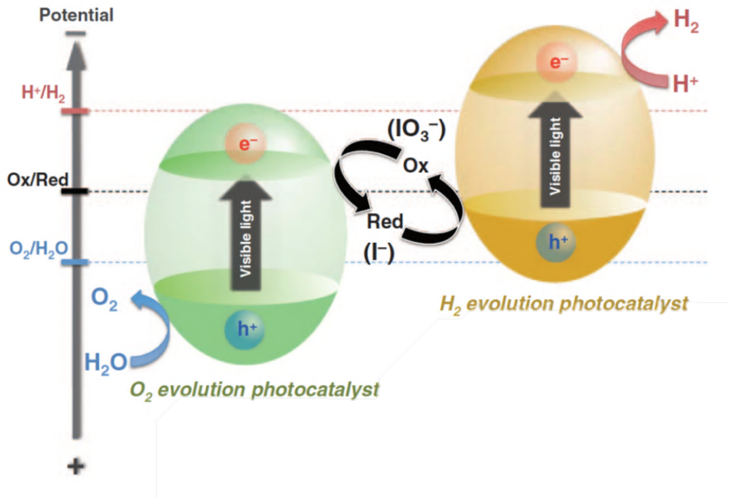
5. different structural properties,
6. their absorption behaviour and
7. the interrelationships between these properties

is essential for the development and commercialisation of these technologies.

Another challenge of current research is the stability of semiconductor materials and catalysts. Here, a further increase in efficiency and durability must be achieved by improving control over the metal structures and properties. In addition, photo-active electrodes must be scalable from laboratory scale to technical scale in order to produce systems with industrial value and maturity [Haussener 2012]. So far, however, only a few concepts for scalable systems have been proposed, such as by repeating basic units.

In addition to the challenges listed above, the individual technologies have other specific problems. Especially for the photocatalytic system in the Z-scheme, the problem of the back reaction has to be mentioned: Here, in most cases, the reduction of the oxidised electron mediator on the H_2 photocatalyst is preferred over the release of hydrogen. The actually desired reaction of hydrogen production takes place to a smaller extent, while the undesired reaction (reduction of the electron mediator) has a large part. This also applies to the oxidation of the electron mediator over the O_2 photocatalyst. In addition, simultaneous gas evolution is a further challenge when both systems coexist in a common aqueous solution. In principle, it is difficult to have both efficient hydrogen and efficient oxygen evolution, but this is necessary for the overall process. For example, a high concentration of electron mediators in the reduced form (Red) is favourable for H_2 development (see Figure 20).

Figure 20: Overview of the water splitting of a Z-scheme photocatalysis with an iodate (IO_3^-) and iodide (I^-) ion redox pair.



Source: Abe 2010

However, this also causes a significant back-reaction of the O_2 development. This is because the back reaction of Red to the oxidised form of the electron mediator (Ox) on the O_2 development photo catalyst is preferred to the O_2 development. On the other hand, a high concentration of Ox is desirable for O_2- development, but again reduces the H_2 development rate. To realise a two-stage water splitting system it is therefore necessary to develop a photo catalytic system with high selectivity for the forward reactions.

3.4 Thermal water splitting with thermochemical cycle processes

The idea of splitting water without electricity and without direct use of light is the focus of research activities in thermal processes. This takes place at temperatures above 2,200 °C. The hydrogen and oxygen must then be separated from each other for further use - for example with ceramic membranes, which are permeable to hydrogen but not to oxygen. However, especially at these high temperatures, this represents a fundamental and as yet unsolved problem. Due to the high temperatures, only very expensive, heat-resistant materials can be used, which has a negative effect on the economic efficiency. However, there is already a company ("H-ion" [Herron 2015]) which offers such a high-temperature technology (>2,500 K) for thermal water splitting by bundling sunlight. However, no information on separation processes and materials is available at present, although the technology is already at the experimental stage.

In order to increase the economic efficiency of thermal water splitting, work is being done on reducing the dissociation temperature. One way to reduce the temperature of thermal water splitting (under 900 °C) is via coupled chemical reactions or thermo-chemical hydrogen production. The thermal energy required for the decomposition of water is covered here by nuclear or solar energy. The lowering of the reaction temperature is achieved by using metal oxides which act as catalysts. The thermal energy requirement can also be reduced if the splitting of water is carried out in so-called thermochemical cycles. The "thermochemical water splitting cycle" usually consists of a high temperature endothermic reaction followed by one or more exothermic steps. Many of these cycles have been described in the scientific literature. Currently, only six of these cycles are proving to be technically and practically feasible. Four of these technologies are based on so-called metal oxide cycles with the elements zinc, iron, manganese, nickel and their oxides and mixed oxides. All six processes can be divided into high temperature (>1000 °C) and low temperature (<1000 °C) technologies [Perkins 2009]. In the following, the two most important thermal cycle processes are described in more detail according to the DLR report "Perspectives of solar thermal processes for hydrogen production" [Pregger 2008].

3.4.1 Sulphuric acid hybrid cycle

The sulphuric acid hybrid process (Westinghouse process) is a two-stage thermochemical cycle for splitting water into hydrogen and oxygen. This cycle is called a hybrid because it involves a high temperature and a low temperature step.

- High temperature step:

The starting material is sulphuric acid, which is first split into water vapour and sulphur trioxide. The resulting sulphur trioxide is then split into sulphur dioxide and oxygen either purely thermally at temperatures around 1,150 °C or, using suitable catalysts, at 850 °C.

- Low temperature step:

After the products oxygen and sulphur dioxide have been separated, sulphur dioxide is fed into an electrolyser. Here the sulphur dioxide is oxidised to sulphuric acid at the anode, releasing hydrogen at the cathode. The cycle process can be described by the following reaction equations:

8. $2\,H_2O + SO_2 \rightarrow H_2SO_4 + H_2$ (electrolysis, 85 °C)
9. $H_2SO_4 \rightarrow H_2O + SO_3 \rightarrow SO_2 + \frac{1}{2}\,O_2 + H_2O$ (thermal splitting, > 800 °C)

Within the framework of the EU project HYTHEC [LE DUIGOU 2007], different operating strategies were investigated on the basis of the variation of the parameters:

- Operating temperature (1,200 °C without catalyst, 850 °C with catalyst)
- catalyst (platinum, iron oxide)
- thermal capacity of the plant (50 MW, 300 MW)
- provision of the required thermal energy (solar, nuclear, solar and nuclear combined)

The investment and operating costs of a plant with a thermal capacity of 50 MW determined in the course of the project are listed in Table 1[Pregger 2008]:

Table 1: Cost overview of a typical sulphuric acid hybrid cycle plant

Investment costs	In 2008 - Unit / million €
Solar system	47.1
Chemical plants	29.1
Electrolysis	38.5
Power generation	6.3
Piping & Installation	13.3
Building	1.83
Direct investment costs	136.2
Security surcharge	13.6
Sulphuric acid	0.015
Land area	2.2

Investment costs	**In 2008 - Unit / million €**
Indirect investment costs	15.8
Total investment	152.0
Operating costs	**In 2008 - Unit / million € per year**
Personnel	0.72
Insurance	3.0
Maintenance	6.1
Water	0.036
Total operating costs	9.9

3.4.2 Sulphuric acid-iodine process

From today's point of view, the improved sulphuric acid iodine process has the highest system efficiency and the greatest potential for future improvements among the cycles mentioned above. In this cycle iodine and sulphur dioxide react with water at 120 °C to form hydrogen iodide and sulphuric acid. After separation of the reaction products, sulphuric acid is split at 850 °C into oxygen and sulphur dioxide and the hydrogen iodide at 300 °C into hydrogen and iodine. The reaction equations are shown below. Only the endothermic catalytic cracking of the vaporous sulphuric acid requires high temperatures of about 850 °C.

1. $9\,I_2 + SO_2 + 16\,H_2O \rightarrow (2\,HI + 10\,H_2O + 8\,I_2) + (H_2SO_4 + 4\,H_2O)$ (120 °C)

2. $2\,HI \rightarrow H_2 + I_2$ (220 - 330 °C)

3. $H_2SO_4 \rightarrow SO_2 + H_2O + \frac{1}{2}\,O_2$ (850 °C)

The most energy-intensive sub-process in the case of this cycle is the separation of sulphuric acid and hydroiodic acid. This has a considerable influence on the process efficiency. In HYTHEC, the use of membranes in the distillation step as a separation process was investigated in particular, in order to achieve the maximum HI concentration in the vapour phase. The system efficiency achieved here was 35%.

It is true that these thermochemical cycle processes have relatively high thermal efficiencies of up to 50%. These are much higher than the efficiencies of the other technologies described in this report, but these efficiency advantages must be compared with the material and process engineering difficulties (including cycle stability) which are still largely unsolved today. It should also be noted that compared to other water splitting processes, such as electrolysis, the use of chemicals as in the two cases presented poses an ecological risk potential.

3.4.3 Outlook thermal water splitting

Critical success indicators for thermal water splitting are

- Temperature reduction through the use of new metal oxides; cost aspects are particularly relevant here,
- Increase of the long-term stability of the metal oxide coating.
- Improvements in plant design for the concentration of solar energy.

Unfortunately, there are no current projects that can be listed as examples to demonstrate process development and possible objectives. From the somewhat older summaries of the European Commission [Directorate-General for Research and Innovation (European Commission) 2005], of the DLR [Pregger 2008] and of Abanades [Abanades 2006] one can get an overview of the research projects that have come to an end. Rough cost estimates for future scenarios in which hydrogen is to be produced from thermo-chemical cyclic processes based on solar energy are put at 10 to 20 ct/kWh. The DLR publication also reported that there are efforts in the nuclear industry to use high-temperature heat from fourth-generation nuclear power plants to produce hydrogen by 2050. However, in the course of the decision in 2011 to phase out nuclear power, another reliable heat source must be guaranteed for the future that meets the thermal requirements of these cycle processes. However, since the technology for direct use of solar energy does not yet have a high and industrially relevant technological maturity level, new innovative approaches to solutions for thermal cycle processes must be analysed in order to advance this technology.

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4 Location factors for the pre-selection of supply paths

In addition to technological parameters, site-specific factors were needed to define and study the supply paths of synthetic energy carriers. For a pre-selection of the supply paths to be analysed, significant regional differentiations were therefore considered, and possible advantageous location factors were determined.

The inputs electricity, carbon (also from biomass) and water have been identified as essential location factors, which should either be available at the production site of the synthetic energy carriers or can be transported there at low cost (e.g., with power lines). These factors were analysed qualitatively and semi-quantitatively. The aim of the analysis was to identify countries with high-value location factors that could be assumed to be the starting point for one of the supply chains in the context of the location comparison. The analysis of the location factors served to reduce the large number of variants of possible supply paths to a relevant selection. Paths without a relevant availability of the necessary inputs were excluded from the analysis. Sites with a favourable availability and combination of carbon/biomass, water and electricity were preferred.

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 renewable electricity supply, the number of full-load hours at the respective location was relevant from a cost and resource perspective. In the case of carbon, the question arose as to the availability of concentrated CO_2 waste gas streams or biomass; in the case of biomass, it is also important which raw material (e.g., wood or biowaste) can be used. In the case of water as a resource, the decisive question was whether it is available in sufficient quantities at the site in question, or whether the supply paths would have to include additional water extraction from the sea.

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 carriers to Germany. The geographical delimitation is shown in Figure 21.

Figure 21: **Geographic system boundary of the EUMENA area for this project**

Source: DLR

First, the distribution and quality of the potentials for renewable electricity from sun and wind were determined, which vary greatly within the area under consideration. This leads to different process chains and plant sizes, e.g., due to a higher number of required electrolysers at lower full load hours.

Most synthetic energy carriers also require carbon, which can be supplied to the processes either as biomass or as CO_2. Besides atmospheric CO_2, concentrated CO_2 (waste gas) streams are also of interest here, which avoid additional cost-intensive concentration of atmospheric CO_2. For this reason, biomass potentials and their distribution were determined for the area under consideration at country level, which could be available to produce liquid and gaseous energy carriers. The biomass potentials identified for fermentation also provide information on the CO_2 potentials from biogas that could be produced in this process (Chapter 6.2).

In addition, the study examined in which countries significant quantities of concentrated CO_2 (flue gas) streams from industry are present. In a climate-neutral energy system, the current main point sources of concentrated CO_2 - combustion of fossil fuels to produce electricity and heat - will no longer be available in the future. The present project therefore considers selected (partly unavoidable) CO_2 emissions from the cement industry as a location factor, which can be assessed as a production factor at the respective location. Just as mentioned before, there is considerable uncertainty as to how CO_2 emissions can change up to 2050, where they will occur in the future and what they will ultimately be used for. As a first approximation, therefore, only the current cement production volumes are considered. CO_2 emissions from households, industry and transport are neglected, as they are no point sources of relevant size. Additionally, the need for additional water desalination was investigated for the MENA region. The location factors were used in the further course of the project to provide a characteristic overview of technically feasible paths to produce synthetic energy carriers.

4.1 Electricity potential from fluctuating renewable energy sources

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

For the supply paths of synthetic energy carriers, regions, or locations with favourable conditions such as high utilisation of installed capacity (high full-load hours) and consequently favourable electricity production costs were of particular interest. These regions were identified using spatially and temporally resolved GIS analyses of the renewable energy potential based on meteorological re-analyses and satellite data. However, in terms of 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 different 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 must 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 carriers [Stetter 2014]. Initially, these requirements had to be identified - e.g., minimum full load hours and grid connection. 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.

The analysis included the following work steps:

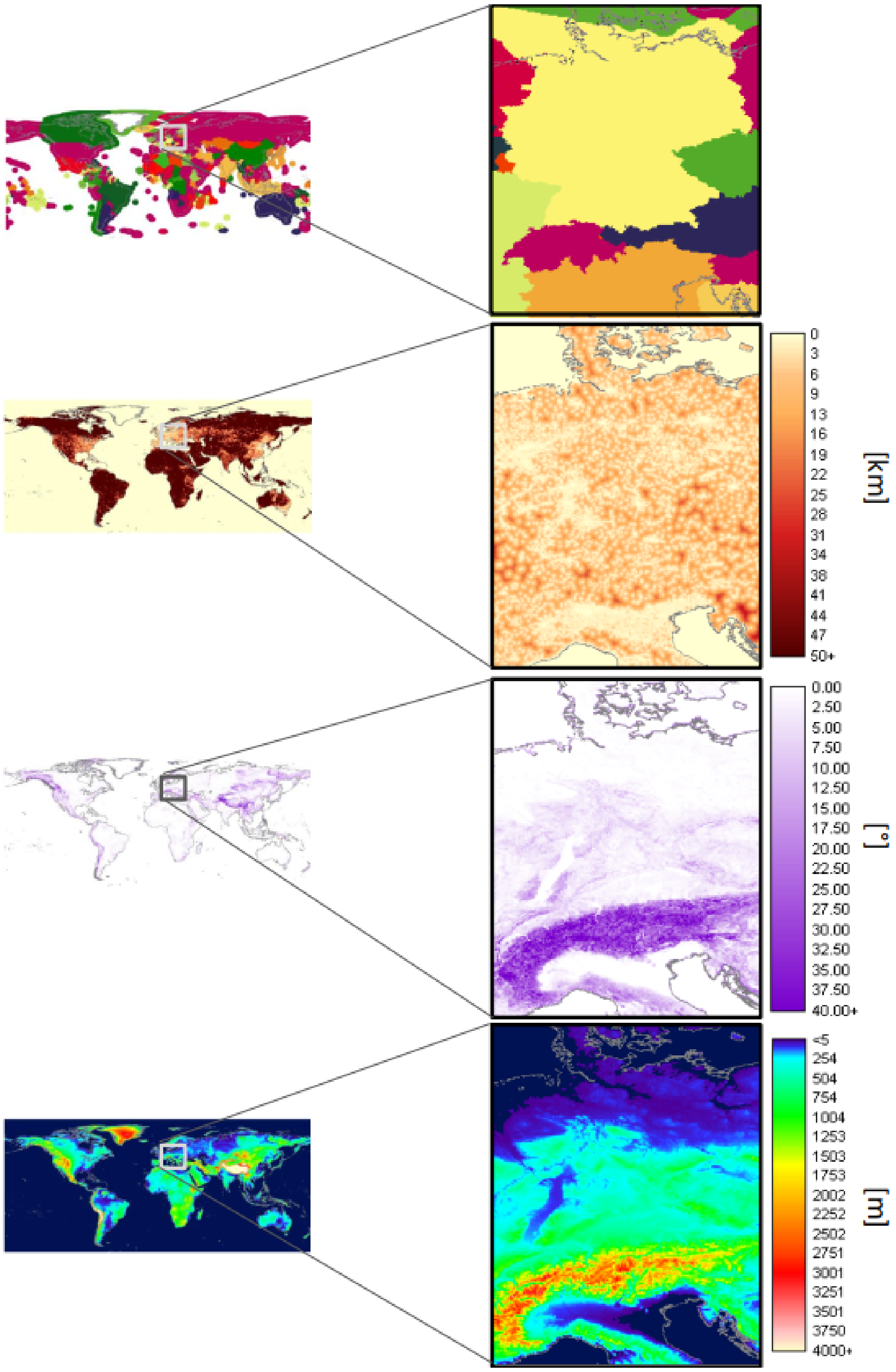
- Identification of exclusion factors (technology-specific)
- Analysis of solar radiation and wind speed
- Definition of reference technologies for wind, PV and CSP and determination of the installable capacity per technology considered for 2050 and calculation of full load hours.

4.1.1 Identification of exclusion factors

A prerequisite for calculating the installed capacity was the determination of suitable areas for the renewable power plant park. For this purpose, globally available information was analysed with a spatial resolution of 300x300 m^2. Figure 22 illustrates parameters used as examples, such as terrain height or distance to settlements.

Different exclusion criteria were defined depending on the technology. For PV, CSP and wind onshore, information on land use, slope inclination, maximum height, minimum distance from settlements, nature conservation areas (based on the World Database on protected areas [WDPA 2010]), geomorphology and hydrology was evaluated which allow or exclude land use for energy generation. For offshore wind the exclusive economic zone, protected areas and water depth were taken into account in order to identify potential areas of use. A detailed description of the method can be found in [Stetter 2014].

Figure 22: Example of global data used in REMix-EnDat.

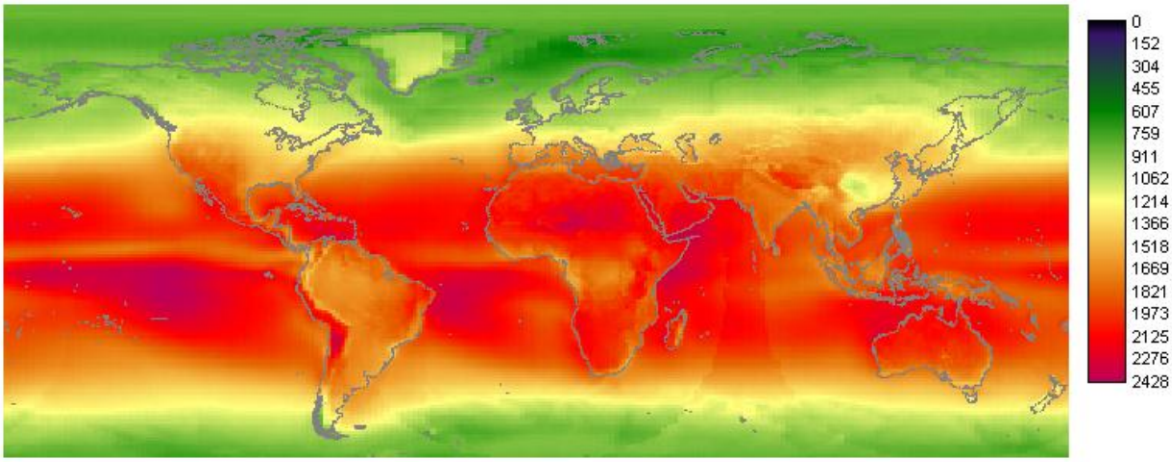


From top to bottom: country-specific exclusive economic zone, distance to settlements [km], slope [°], elevation above sea level [m].
Source: DLR

4.1.2 Analysis of the availability of solar radiation and wind speed

Globally available data sets in REMix-EnDAT were used to determine the available solar radiation and wind speed. On the one hand, a long-term data set is important to take into account the annual variability. On the other hand, the information must be available with high temporal resolution in order to calculate the hourly electricity generation per technology. For PV and CSP, global radiation and direct normal radiation were analysed. According to Stetter [2014], the data basis is the NASA SRB data set shown in Figure 23

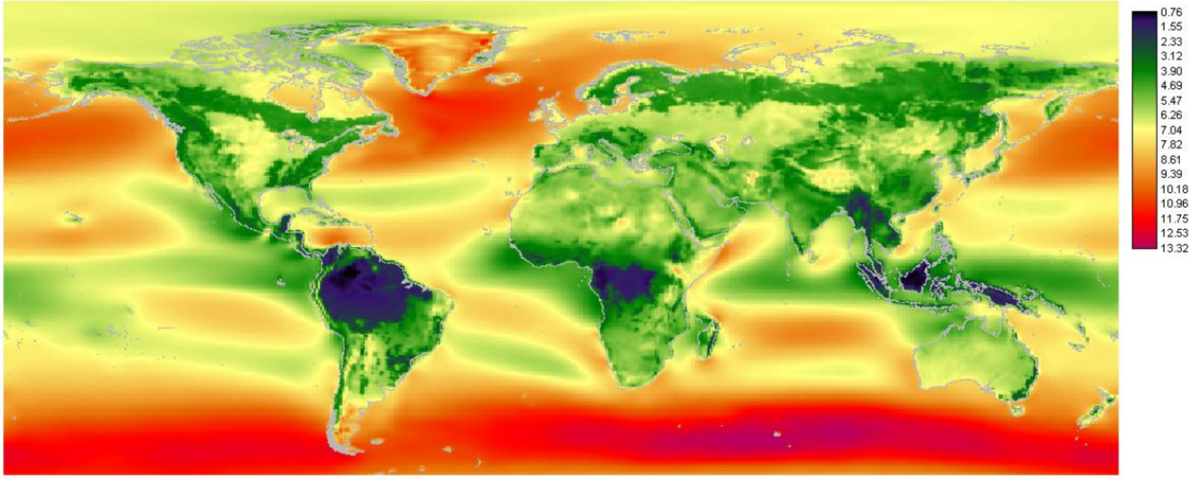
Figure 23: **Long-term averaged annual sum of global radiation [kWh/m²], NASA SRB**



Source: DLR, Stetter 2014

Similarly, wind energy was determined on the basis of wind speeds. The analysis is based on the MERRA data set [Stetter 2014], which is shown in Figure 24

Figure 24: **Long-term annual mean wind speed at a height of 50 m [m/s], MERRA [Stetter 2014].**



Source: DLR, Stetter 2014

These wind and solar data were the basis for calculating technical potential.

4.1.3 Determination of installed capacity and hourly electricity production

On the basis of the data sets described, the installed capacity and hourly electricity generation were calculated for each technology under consideration. This was done for the year 2050.

After the analysis of the exclusion factors, the suitable areas per technology were available. On the basis of technical parameterisation of sample plants, the technology-specific area output for wind and solar was then determined in order to obtain a statement on the maximum installable capacity per km^2 per generation technology. The underlying parameters for wind energy, PV and CSP plants in REMix-EnDAT are shown in Table 2

Table 2 Technical parameters for the determination of specific area outputs for wind and solar according to [Stetter 2014]. [11]

Technical parameters	Unit	2020	2050
PV module efficiency	%	17.3	18
PV loss factor decentralised	%	15	15
PV loss factor large plant	%	10	10
PV availability factor	%	98	98
CSP efficiency of the power plant	%	37	37
CSP storage efficiency	%	95	95
CSP availability factor	%	95	95
Wind onshore turbine power	MW	3.4	5.5
Wind onshore rotor diameter	m	102	103
Wind onshore rotor height	m	122	132
Wind offshore turbine power	MW	6	12
Wind offshore rotor diameter	m	136	192
Wind offshore rotor height	m	102	140
Wind loss factor	%	15	15
Wind availability factor	%	95	95
Wind distance factor (X * rotor diameter)		6	6

Based on Nitsch [2012], Stetter [2014] calculated the technology-specific installable capacity per area and year, which are used for the calculation of the hourly electricity generation. For 2050 this resulted in the following parameters (Table 3):

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[11] The technical parameters applied here deviate in part from the parameters within the technical modules in Chapter 2, as a new parameterisation of REMix EnDat is not part of the project plan. However, they are sufficiently similar to fulfil the purpose of a site analysis in the sense of the project.

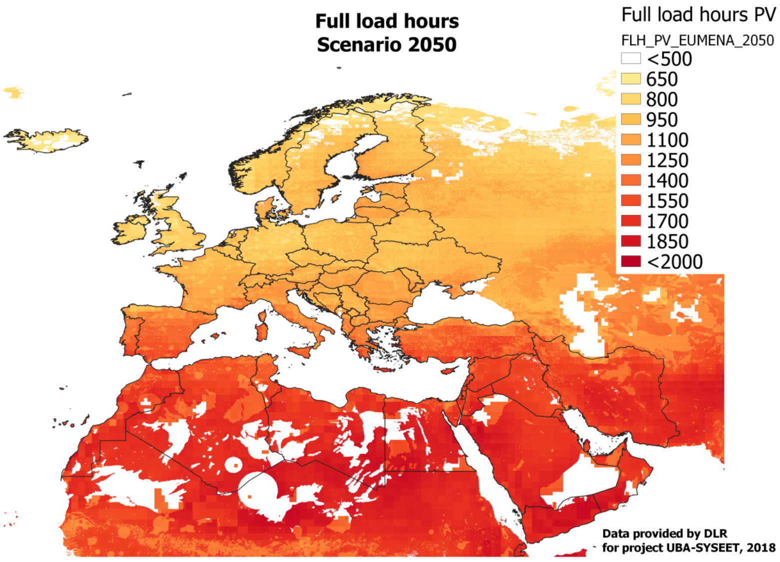
Table 3: Specific area output 2050 for wind and solar energy [Stetter 2014].

Technology	Unit	Specific technical area output
PV	MWel/km^2	152,2
CSP	MWth/km^2	176.6
Wind on/offshore	MWel/km^2	10.4

Based on the above assumptions, the power plant module within REMix-EnDAT calculated the hourly electricity generation per technology. In doing so, the electricity yield of wind turbines additionally takes into account the different wind speeds at rotor height, which leads to a considerably higher energy production at sea. Subsequently, the annual electricity generation and the installed capacity were used to determine the full-load hours relevant for the LCA by dividing the annual yields by the installed capacity.

For each of the technologies under consideration - PV, CSP, wind onshore and offshore - a data set of full load hours is thus available. These are shown in the following figures.

Figure 25: Visualization of the calculated full load hours for the year 2050 for PV

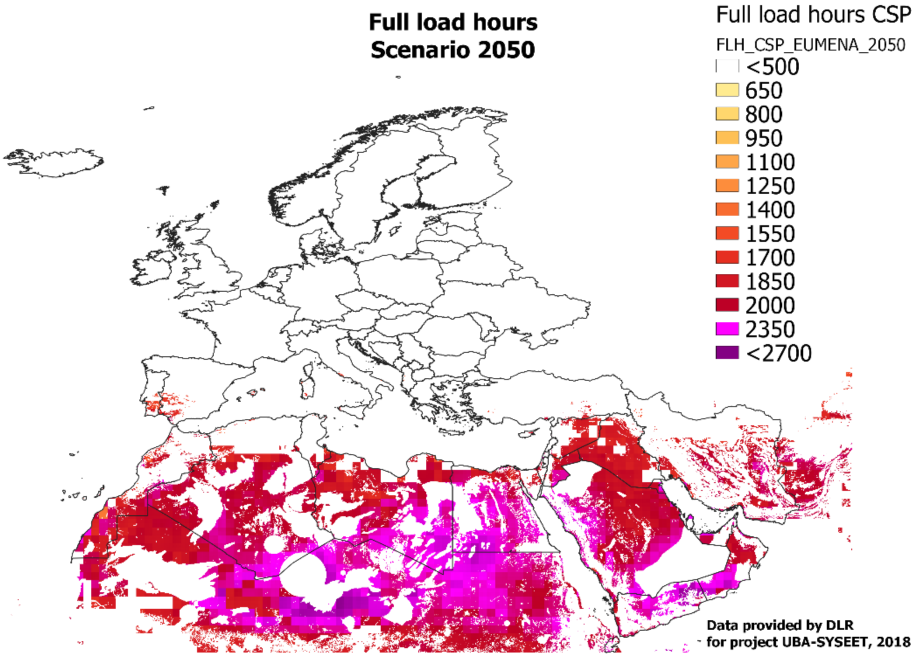


Source: DLR

PV is available throughout the EUMENA region, but with quite different yields: In Europe, PV provides full load hours (FLH) from 900 to 1100 h/a, while in the MENA region, 1200 h/a and in extreme cases up to 1800 h/a are achieved.

CSP, on the other hand, is only usable on the southern edge of Europe and in the MENA region; the identified usable FLH from 1800 to 2500 h/a do not yet take storage into account (solar multiple 1.0). With the appropriate configuration with storage for up to 14 h (solar multiple 3.0), as envisaged in the project, over 7000 h/a can be achieved. These two options are shown in Figure 26

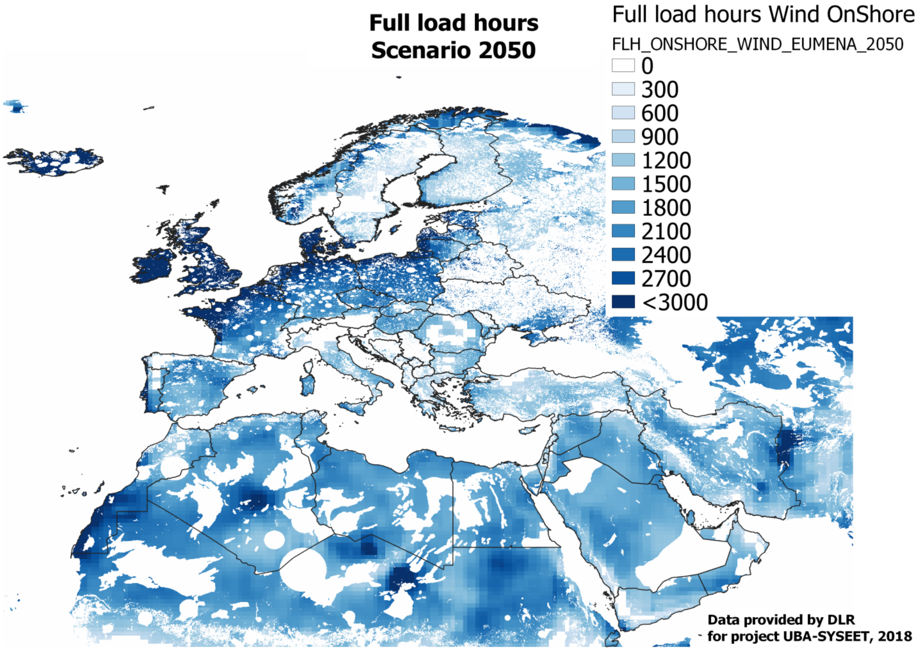
Figure 26: Visualization of the calculated full load hours for the year 2050 for CSP



Source: DLR

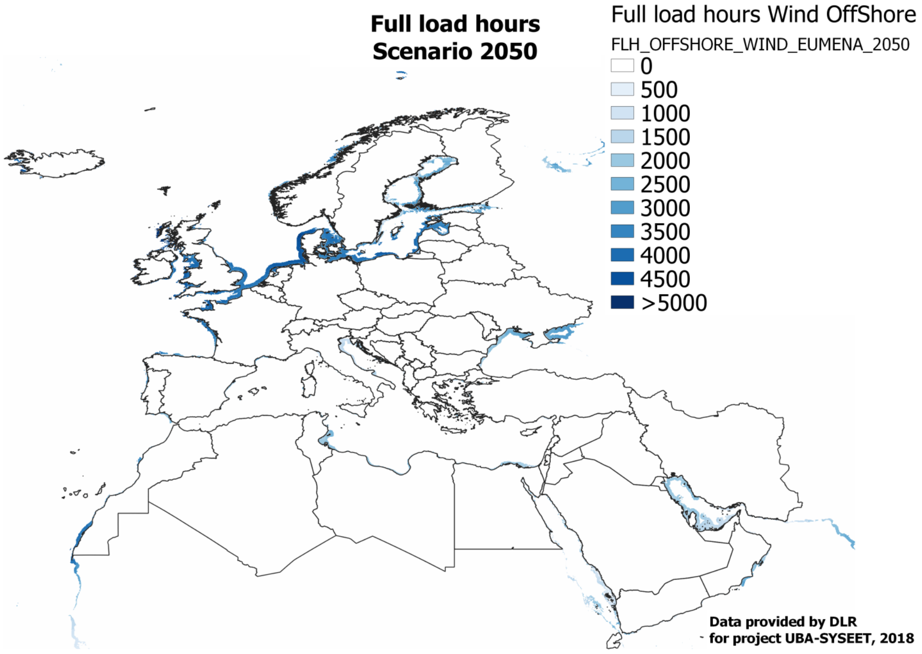
For wind power the differences are also very pronounced. Onshore FLH of 2300 to 2900 h/a can be achieved in the entire EUMENA region at various suitable locations especially near the coast. Many areas reach 1800 to 2300 h/a. Offshore, much more can be achieved, around 3500 to 4500 h/a, but the overall potential is limited to a few coastlines in Central and Northern Europe.

Figure 27: Visualization of the calculated full load hours for the year 2050 for wind onshore



Source: DLR

Figure 28: Visualization of the calculated full load hours for the year 2050 for offshore wind



Source: DLR

The supply paths in this project did not select precisely localised sites but used data for an averaged good site in one country. To this end, full-load hourly 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. The selection of the countries considered was made together with the selection of the supply paths and is described in Chapter 5.2. Table 4 shows the full-load hours thus determined for the countries and technologies selected as locations for solar and wind energy.

Table 4: Mean full load hours for the upper 50% of full load hour potential curves for some selected countries and technologies

Country	PVground	CSP (without storage)	CSP (SolarMultiple 3)	Wind Onshore	Wind Offshore
Morocco	1729	2063	6189	2946	3928
Saudi Arabia	1777	2179	6537	1870	1963
Germany	958	0	0	2963	4234

4.2 Biomass

Sufficient input must also be ensured for the biomass-based technology modules for the production of liquid and gaseous hydrocarbons. On the one hand, these are solid biomasses, 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. For both, possible availabilities were determined from literature data to narrow down the countries. 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 carriers that can be produced.

The availability of biomass was compared between countries only on the basis of orders of magnitude. On the one hand, biomass produced outside Germany can go into the production of synthetic energy carriers in these countries. On the other hand, biomass imports from these countries with subsequent processing in Germany are also conceivable for a few types of biomass. However, many studies, such as the long-term scenarios from [Nitsch 2012], the "Klimaschutzszenario 2050" [Öko-Institut 2015], and studies by the Federal Environment Agency ("Germany in 2050 – a greenhouse gas-neutral country " [UBA 2014], RESCUE [UBA 2019]) assume that a substantial biomass import does not constitute a sustainable strategy due to the limited availability worldwide.

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 quantitative supply 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 a 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].

In the scenarios of the DBFZ [2010], possible availability of agricultural biomass with priority for food production is only given in the so-called "bioenergy scenario" (since this study explicitly deals with the question of import possibilities to Germany, it is given special consideration here). To narrow the geographical range, maximum values of possible availability were used, especially according to [DBFZ 2010].

- The following biomasses were considered:
  - Biogenic residual/waste materials
  - Forest residue wood
  - Liquid manure (slurry, no solid manure)
  - Cereal straw
  - Municipal biowaste (for biogas fermentation)
  - Industrial wood scrap (bark, sawmill by-products) and wood scrap

- Cultivated biomass:
  - Maize
  - Energy wood (SRC = short rotation coppice)
  - Miscanthus

4.2.1 Germany

Biogenic waste/residual materials

The possible availability of biogenic waste and residual materials in Germany was examined in detail in the study [BioRest 2019]. Data from this study are presented in the technology profiles in Chapter 2.2.2

Cultivated biomass in Germany

Potential availability of cultivated biomass in Germany for energy use was taken from [Fritsche 2004] [Nitsch 2004, Nitsch 2012] and [DBFZ 2010].

4.2.2 Potential availability EUMENA

Transportability of biomass and biomass-based energy carriers

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

Possible availability in the EU: National Renewable Energy Plans (NREAPS)

For the EUMENA region, possible 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.

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] was used as a basis, partly supplemented by updates and the new Croatian NREAPs.

On this basis, the possible availability of **wood biomass in France, Italy, Finland and Sweden and of cultivated biomass (including SRC) also in France and Italy** should be highlighted. If other biomass, especially for the import of processed biomass as an energy source, is to be taken into account, **Italy stands** out **in particular in the area of agricultural by-products and biowaste.**

4.2.3 Other potential availabilities in the EUMENA region

Other studies consider the area outside the EU but should also be seen as a complement to the potential EU availabilities.

Cultivated biomass and grassland growth

The DBFZ [2010] "bioenergy scenario" considers grassland growth and cultivated biomass. For the cultivated biomass, it is assumed that the area is occupied by plants with a high energy potential. In the temperate latitudes, the available areas are assumed to be covered with one third of the CDP, with sugar beet, silage maize (EU only) and the highest-yielding cereal or oil crop in descending order of priority. The possible energy availability of the SRC is not included here, but under forestry biomass (see below). The data taken into account therefore primarily represent **possible availabilities for fermentation.**

In contrast to the above-mentioned possible availability of NREAPs, Spain is presented here with a higher possible availability than Italy. France is also attributed a high possible availability here. Outside the EU, in the EUMENA area especially Ukraine should be highlighted.

Forestry biomass including short rotation coppice (SRC)

In the DBFZ study, forest biomass in the EUMENA region was primarily considered for Europe. The possible availabilities include on the one hand the technical energy wood availability as the difference between the possible projected availability of raw wood and the consumption of materially used round wood. On the other hand, the above-mentioned possible availability from SRC is included here. In addition to the NREAPs considered above, the United Kingdom (no data in NREAPs) and Norway also have significant possible availability [DBFZ 2010].

Residuals

International potential availability of residual materials beyond the EU could not be numerically determined from the literature search. However, the DBFZ study includes possible technical availabilities of individual residues for the period 2003 to 2007 on the basis of mapped size classes. These are used here as an approximation. For **straw,** in addition to Germany and **France, the Ukraine, Turkey and Egypt should be** highlighted. In the field of **animal excrement, Great Britain, France and Spain** should be mentioned. In the area of **municipal waste, Great Britain, France, Italy and Turkey** had the greatest possible availability in the period of the DBFZ study shown. With regard to **wood biomass, France and Finland** (forest and industrial residues) and **Sweden** (forest residues) are particularly noteworthy [DBFZ 2010]. However, the MENA region has not been given much consideration in terms of residual wood overall.

Overall, **for the EU, the possible availability in France**, covering both **agricultural crops and residues and wood,** can be highlighted. **Outside the EU, Ukraine (straw, cultivated biomass) and Turkey (straw, municipal waste)** seem particularly worth mentioning. In **North Africa,** only the possible availability of **straw in Egypt stands** out. Here in particular, however, the data used were patchy.

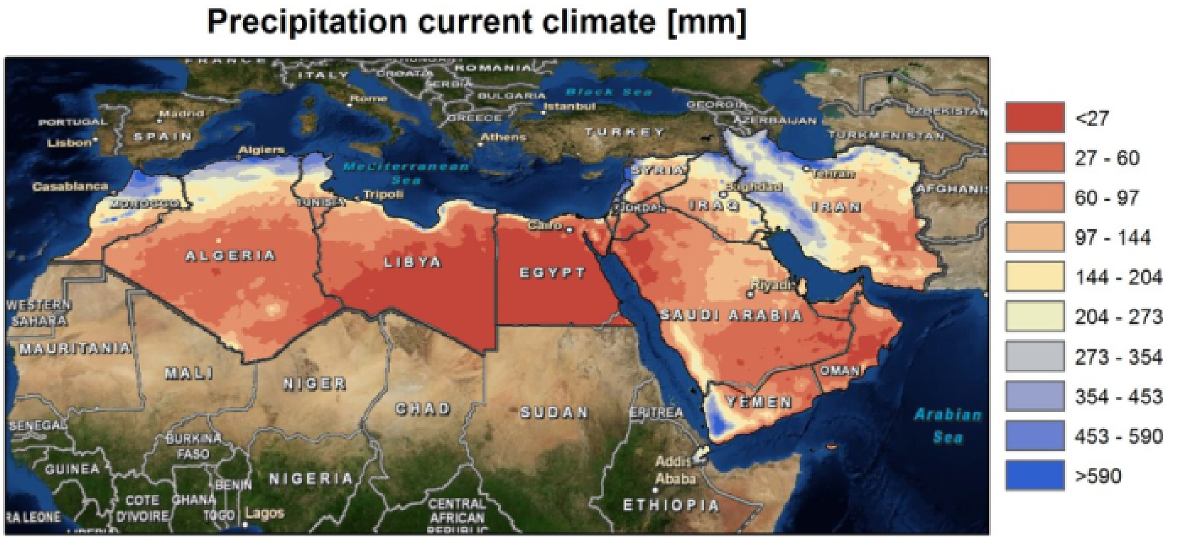
4.3 Water supply from desalination for electrolysis

The supply of many synthetic energy carriers requires additional water, especially for electrolysis. This is taken into account in life cycle assessments, but also represents a location factor for the selection of supply paths to be considered. In addition to the existing surface and ground water potentials, seawater desalination using solar energy can play a significant role. This applies in particular to regions that will have to deal with water shortages in the future (or even today).

The water demand of a prototype electrolysis reference plant has already been described in the technology profiles in Chapter 2.1.1 and characterised with regard to quality requirements. Not everywhere the additional water demand can be covered by conventional water supply. There, additional water must be provided via seawater desalination as described in Chapter 2.2.4. Furthermore, the sites for which additional water desalination plants could become relevant were qualitatively derived by comparing water availability and the development of water consumption. For all supply paths located in the region identified in this way, the life cycle assessments and cost considerations each include a corresponding seawater desalination plant.

To analyse water availability in MENA, DLR has already carried out studies on possible perspectives and costs [Moser 2015]. As part of the "MENA Regional Water Outlook" project, long-term scenario analyses for water consumption in various MENA countries were prepared [Verdier 2011], which were included in the assessment in this study. Precipitation is typically low in the countries of the Sun Belt. For the countries of the MENA region, current analyses show that average annual precipitation is often close to 0 mm/a (Figure 29). The exceptions are a few mountainous regions in Morocco and Iran, where precipitation reaches up to 600 mm/a.

Figure 29: **Annual precipitation in the MENA region (model year 2011, MENA Regional Water Outlook)**

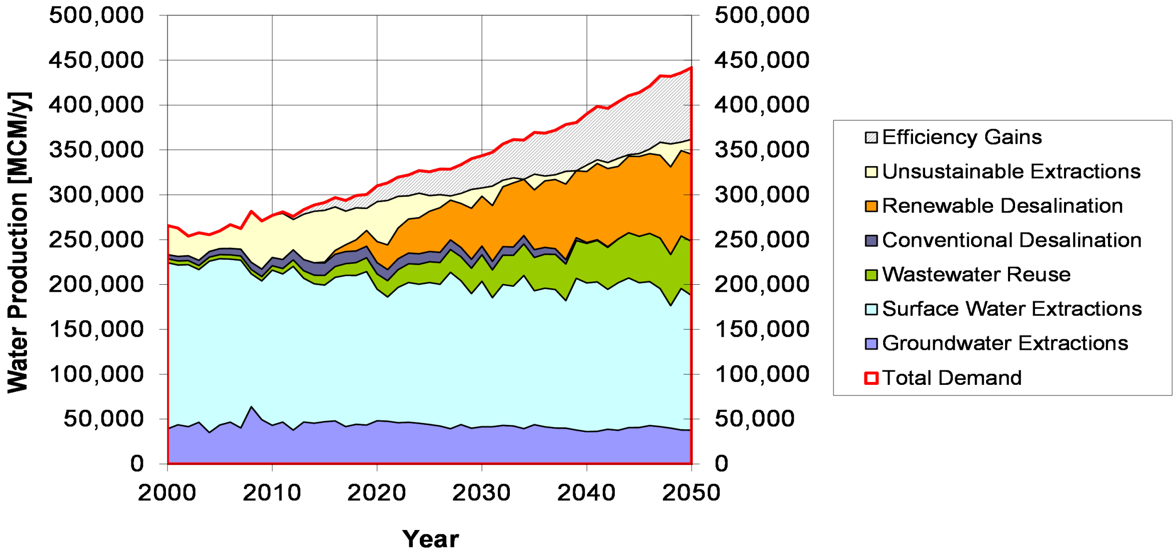


Source: Verdier 2011

In general, it is not to be expected that surface water or groundwater will be available to produce synthetic energy carriers in this region in the future. Forecasts based on climate models indicate an even more difficult water situation, as a reduction in precipitation of up to 20% is expected for the year 2040 and beyond. On the other hand, the population of the MENA region is expected to grow from currently about 400 million to about 600 million in 2040 [UNPD 2015]. In view of the limited availability of other water sources, the water supply must in any case be secured by measures such as increasing efficiency in water distribution, shifting agricultural use, wastewater treatment and reuse, and seawater desalination with renewable energies.

Figure 30 shows a scenario of future water demand in MENA and a possible supply infrastructure that would have to be built in the future [Verdier 2011]. The scenario indicates that there will be a significant reduction in the medium and long-term availability of surface and groundwater. This could result in a serious supply shortfall, which could affect the entire region. The scenario shows that in MENA after 2015 the drinking water supply in many countries will have to be secured by new desalination plants. According to this study, desalination with renewable energies will provide a large share of water production in the medium and long term, although, according to the assumptions made, it is the last economic option. Due to the increasing scarcity of water in the future, water is therefore generally regarded as a limiting factor for the supply of synthetic energy carriers in the MENA region. Consequently, additional seawater desalination must be taken into account for all supply paths in this region.

Figure 30: Water supply scenario for the MENA region



Source: Verdier 2011

In the context of this study, the additional water demand for the supply of synthetic energy carriers in the MENA region is generally covered by increasing water production from seawater desalination. For Europe, the present project does not assume a structural water shortage and thus sites with sufficient water supply, which is why the life cycle assessments of the supply paths were configured here without desalination.

4.4 Availability of CO_2 as a carbon source

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 carriers, however, concentrated sources are always being discussed - especially from industry and biogas production.

4.4.1 Carbon potentials from industrial processes using the cement industry as an example

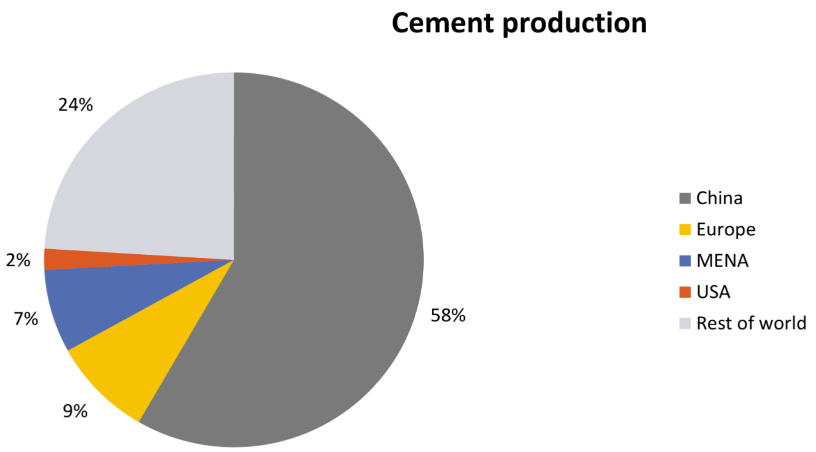
After electricity generation in fossil power plants, industry is the largest stationary and concentrated source of CO_2 worldwide [IPCC 2005]. Today, industrial processes account for 6% of global CO_2 emissions [IEA 2017]. While CO_2 emissions from the use of fuels can be replaced by alternative fuels, this only applies to a limited extent to process-related emissions. Industrial processes generate raw material-related emissions, e.g., through the deacidification of limestone in the cement industry. These raw material-related emissions will continue to exist in the future and represent a long-term carbon source. During the transformation to a climate-neutral economy, it is expected that other concentrated CO_2 point sources, e.g., in oil refineries, in steel and ammonia production as well as in natural gas processing and hydrogen production by steam reforming, will decrease by 2050 due to the conversion to low-carbon processes and eventually disappear completely. This study therefore focused on the main source of hardly avoidable CO_2, cement production, which provides waste gas streams with a relatively high CO_2 concentration of 15 - 35% [EU Commission 2011, Last 2011].

On industrial CO_2 capture, research and development is currently focusing on the selection of suitable processes and initial demonstration projects. Realistically, only very few projects can be expected in the next few years. Industrial CO_2 will therefore only be available to produce storable energy carriers in the medium to long term.

However, the total quantity is less relevant for the estimation of possible supply paths. The primary goal of the analysis is therefore a qualitative or semi-quantitative selection of plausible locations. Therefore, current production was chosen as an indicator for the site selection of the supply paths. The quantitative availability of climate-neutral carbon was estimated based on statistical data on industrial activities in the EUMENA region at country level. In particular, statistics from industry associations and production statistics were used.

The cement industry is the largest industrial source of CO_2 emissions. Cement plants alone are responsible for about 7% of stationary CO_2 emissions. During the burning of cement clinker in the rotary kiln, considerable quantities of CO_2 are released not only from the burning of fuels but also from the deacidification of limestone (and clay). These quantities account for about 2/3 of the total emissions and cannot be completely avoided [Romano 2013, VDZ 2016]. At the same time, the emissions from the burning process will also remain in the future. In 2014, about 4.3 billion tonnes of cement were produced worldwide, about two thirds of this in Asia (Figure 31). The EUMENA region accounted for about 700 million tonnes of production.

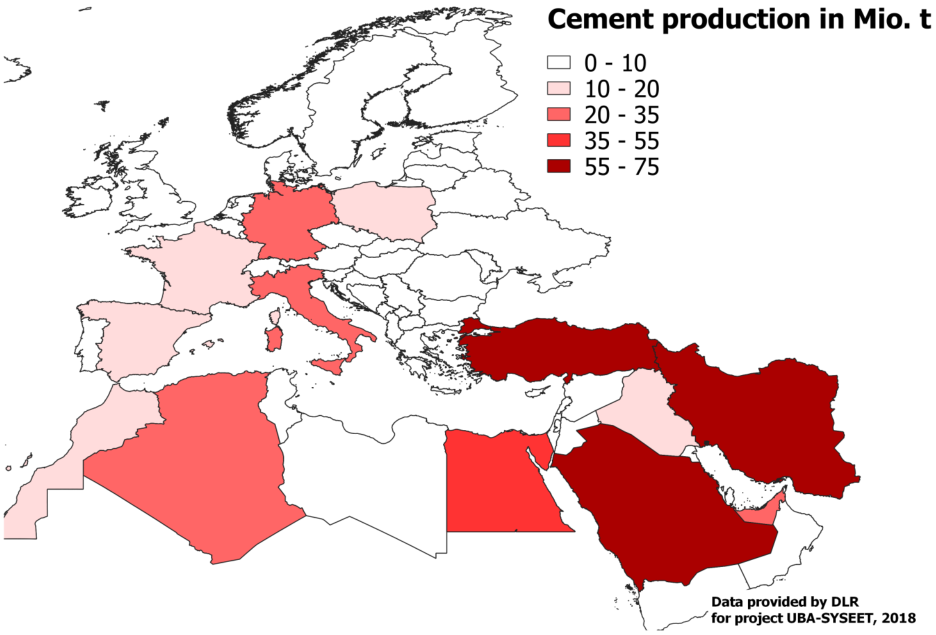
Figure 31: EUMENA shares in global cement production 2014



Source: DLR, based on GlobalCement 2017, USGS 2017

Within the EUMENA region, cement production is spread over many locations. Figure 32 shows a classification of the current production of cement in the EUMENA area under consideration.

Figure 32: Classification of cement production in EUMENA



Source: own figure, DLR

The analysis shows that in a relatively large number of countries in the EUMENA region there is the possibility of using CO_2 from cement production to produce synthetic energy carriers. Estimates of which emissions from cement production are unavoidable and how they can be reduced in the future are relatively uncertain [IPCC 2006; Vogel et al 2011; VDZ 2016; UBA 2018].

Since the emissions are very concentrated at the rotary kiln in the plants, it seems relatively easy to use the CO_2. Depending on the process, around 60-85% of the emissions could be captured in the overall process and used as a source of CO_2. Most projects for the capture of CO_2 from the cement industry are still in the development and demonstration phase and are not yet available to produce synthetic fuels. Since neither future developments in the cement industry can be analysed within the present project nor the effects of various process optimisations can be investigated within the project framework, an estimation of future CO_2 potentials would be very uncertain. Moreover, no specific emission factors are available for many of the countries under consideration. Therefore, in this study, the total production volume of cement was initially used conservatively as a first approximation for the availability of CO_2 for further processing into synthetic energy carriers.

Table 5 shows the nine countries with the highest production (2014). Behind the front runner **Turkey,** a high concentration of cement production in the Middle East is striking. The countries of the EU fall behind.

Table 5: The nine countries with the largest cement production in the EUMENA region

Country	million t
Turkey	71
Iran	66
Saudi Arabia	57
Egypt	49
Germany	32
United Arab Emirates	28
Italy	21
Algeria	21
France	18

Source: USGS 2017

To cover the entire area under consideration, the selection of sites where industrial CO_2 is used was concentrated on the main producers in the respective sub-region. For Europe these are **Turkey, Germany** and **Italy**. For North Africa, **Egypt** and **Algeria** could be considered, and in the Middle East (ME), **Iran, Saudi Arabia** and the **United Arab Emirates** were available for selection.

4.4.2 CO_2 from biogas

In addition to industrial CO_2 sources, fermentation processes in combination with subsequent CO_2 capture are also an **option for using** 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 amount of biogas produced. Limiting factors are a minimum plant size of the biogas upgrading plant and thus the biogas plant for economic reasons, the proximity to the gas grid for methane injection as well as the presence of a waste heat source at the site for one of the basically possible CO_2 capture processes (chemical absorption).

For the direct use of carbon from biomass, the possible availability for the purpose of this study was presented in chapter 4.2 This also includes the biomasses that can be used for fermentation. For animal excrement, municipal waste, the **UK, France, Spain, Italy** and **Turkey** are mainly mentioned, which could thus also provide CO_2 from biogas. However, no quantification was made here.

4.5 Results of the preliminary site analysis

In the EUMENA region, the availability of renewable electricity from wind and sun, biomass, CO_2 from the cement industry and water differ strongly depending on the location, and thus served to select different locations and transport chains for the supply paths. These site factors within a chain do not necessarily have to be available at the same site. 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, biomass and CO_2 from the cement industry are only worth transporting to a limited extent. 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, the 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 European sites near the coast offering full load hours of 2,500 to 2,900 h/a, while in MENA slightly lower full load hours of 2,100 to 2,400 h/a are possible.

At the particularly favourable locations

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

In the second case, the potential availability of **wood biomass** (forest residues, wood scrap, industrial residues) **within the EU means that France, Italy, Finland and Sweden are the** main countries of concern. In addition, **Turkey, Ukraine and Egypt have** relevant quantities of straw. For **cultivated biomass, France, Italy and possibly Spain** are also considered within the EU and **Ukraine** outside the EU. **Fermentable residues** are mainly available in **Italy, France, UK and Spain**, and outside the EU in **Turkey** (municipal waste). At the same time, they also generate relevant **amounts of** CO_2, which become available in **biogas production** and can also be used as a carbon source.

In addition, CO_2 emissions from industry also complement the carbon sources used for the production of synthetic fuels. In the case of the **cement industry,** there are availabilities 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 quantities of CO_2 are produced mainly in **Egypt** and **Algeria.** Outside these identified countries, it is mainly possible to define supply paths that rely on the capture of CO_2 from the air. These delivery paths then also take into account the overall probably limited amount of concentrated CO_2 available in a decarbonised energy system.

4.6 References

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5 Life cycle assessment

5.1 Method, specifications, impact categories

5.1.1 Scope of investigation

In this part of the study, quantitative or qualitative analyses and evaluations of the selected supply paths were carried out from an environmental and resource perspective. Since a critical review of these results is not part of the project's scope, this study does not fulfil all the requirements of the ISO standards for life cycle assessments (LCA) ISO 14.040 and ISO 14.044. In principle, however, the methodology is closely following these standards.

Functional unit

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

Geographical scope

The energy carriers are delivered “to the filling station" or “to the gas connection" at a single final destination in the centre of Germany (Chapter 5.1.3.3). Energy production, electrolysis, biomass cultivation and processing, CO_2 supply and hydrocarbon synthesis are located in Germany or, depending on the supply path, in countries within the EUMENA area.

Time scope

Three different time periods were considered in this study: The current situation based on the reference year 2015, a medium-term future development labelled as "year 2030" and a long-term development labelled as "year 2050". Data describing the current state of the art were used for the year 2015, while the situations in 2030 and 2050 were estimated using estimations for the future development of electrolysis and synthesis technologies and the general industrial landscape. Detailed information on the applied estimations is given in Chapter 5.1.2.

System boundaries

For this study, a cradle-to-product approach was applied, representing a subsystem of a complete cradle-to-grave LCA. Thus, all processes along the processing chain from the extraction of raw materials to the provision of the product (FT fuel, methanol, synthetic natural gas, biogas, hydrogen) in Germany are considered. Subsequent conversion processes, especially the utilisation phase, are outside the system under investigation.

The system under consideration includes the following processes for the production 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, pelletising), product synthesis and preparation, if necessary,
- Extraction and transport of fossil fuels for electricity and/or heat production,

- Infrastructure and operating materials (catalysts, electrolytes, scrubbing solutions) for plants and means of transport, in particular for the provision of renewable energy, electrolysers and synthesis plants,
- Upstream processes of all materials used in the above-mentioned processes,
- Emission of CO_2 from carbon bound in the energy carrier at the end of life,
- Not included in the mentioned system boundaries are the emissions and waste generated at the end of the product's life – except for CO_2 from the carbon bound in the product.

The associated individual processes or modules were parameterised and connected within the LCA and material flow software Umberto. The calculation of the resulting models for the supply paths yielded the corresponding resource requirements and emissions (life cycle inventory) for the reference years 2015, 2030 and 2050. This calculation served as the basis for the impact assessment.

5.1.2 Infrastructure and background system

In many investigations for products that are produced in high volumes, the provision of the capital goods – the so-called background system – is not included in the system boundary, as its influence on the result is usually marginal. In such investigations, the use of fossil fuels and raw materials usually dominates the result. However, in some cases the provision of the capital goods may represent a large share of the total environmental impacts of the corresponding product. This is the case for plants with a low throughput compared to the material used in the construction of the plant or for plants that generate energy from renewable sources.

In this project, the provision of infrastructure for plants and transportation was taken into account in the LCA, as the synthesis processes for the year 2050 rely almost exclusively on renewable energy sources.

The data for the construction of today's infrastructure (2015) were largely taken from the EcoInvent 3.5 LCA database and supplemented by literature research. The results of the UBA project "Update and evaluation of life cycle assessments of wind energy and photovoltaic plants considering current technological developments" [UBA 2019a] were used for modelling the construction and operation of wind power and PV plants.

The environmental impacts of the processes under consideration are expected to change during the transformation to a largely carbon-neutral economic system. This transformation is supposed to be almost completely established in Germany by 2050. 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 for industrial and transportation purposes will be replaced by materials with a lower carbon footprint. Energy efficiency will increase in all sectors of the economy.

Numerous processes in the models of the LCA and material flow software Umberto were adapted for the calculations of the reference years 2030 and 2050 in order to estimate the influence of the changes in these background systems on the total environmental impacts associated with the production processes considered in this study. Data for these changes on the path of transformation were taken from the parallel study "Resource-Efficient Pathways to Greenhouse-Gas-Neutrality - RESCUE" [UBA 2019b].

In particular, the following processes were modelled in the present 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),
- Plastics production (covering the raw material and process heat requirements with regeneratively produced methane).

The same transformation path as in Germany was assumed for the energy systems and production processes within the EU; a similar development with a ten-year time lag was assumed for the rest of the world.

5.1.3 General assumptions within the supply paths

5.1.3.1 Energy Management

Most of the synthesis processes under consideration are exothermic, such that heat is released during the production processes. The heat can be used for various other process steps (e.g., CO_2 capture, biomass conditioning, high-temperature electrolysis) or in part for electricity generation.

A ranking of heat utilisation within the processes was established within the framework of this study.

In (P)BtL processes:

- Heat with a temperature above 200 °C is used for biomass conditioning (drying, pelletising). Surpluses are used as district heating,
- Heat with a temperature below 200 °C is used for the generation of electricity, which may flow into the electrolysis.

In PtL and PtG processes:

- Heat with a temperature above 200 °C is used in high-temperature electrolysis or, if not applicable, for the separation of CO_2. All further heat is used for the generation of electricity generation, to be used within the electrolysis.
- Heat with a temperature below 200 °C is used primarily in a high-temperature electrolysis, if such an electrolysis is provided for, and secondarily for CO_2 capture.

External use was assumed for all electricity and heat that are not fed back into the process chain. These energy products are associated with environmental burdens allocated according to their exergy content (Chapter 5.1.3.4).

5.1.3.2 Full load hours

The modular structure of the supply paths allows to determine 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 available electricity grid mix. It is also conceivable that the plants will only be operated when there a surplus of renewable electricity is available (grid-supportive).

These cases are not all reflected in the present study due to the corresponding increase in number and complexity of the supply paths. To define the range of these cases of operation, the ecological and economic calculations in this project were carried out in two main cases:

1. Operating case "full-load hours synthesis plant": The electrolysers, CO_2 capture and synthesis plants run for the technically maximum possible annual operating hours (usually around 8000). Nevertheless, in mathematical terms they are supplied from the assigned power source. The potentially required storage units (electricity, H_2, CO_2) are therefore neglected.
2. Operating case "full-load hours power source": The electrolysers, CO_2 capture and synthesis plants only run during those operating hours corresponding to the full-load hours of the assigned power source.
   Example: PV plants in Morocco reach an average of 1729 full-load hours per year. Consequently, the synthesis plants are only operated for this time each year. Potential technical consequences of intermittent operation (catalyst ageing, efficiency of start-up processes) are neglected.

Additionally, supply paths for the products Fischer-Tropsch fuel, methanol and synthetic natural gas were calculated using the respective electricity mixes of the reference years.

5.1.3.3 Transport

Some simplifying assumptions were made for the transport of CO_2 and the products:

- CO_2 is not transported. Synthesis plants are either built near the CO_2 sources or CO_2 is captured from the ambient 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 run on fossil fuels in 2015 and 2030, and on Fischer-Tropsch fuel in 2050.
- Ships used to transport the products will be run on fossil fuels in 2015 and 2030, and on the respective product generated in the supply path in 2050.
- 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.

5.1.3.4 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 issue is addressed by using allocations. Since a single scientifically clear allocation method is not available, it is necessary choose allocation rules that must not violate the basic laws of science (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 wherever possible. Heat energy and electrical energy are 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") is taken into account, e.g., the application of fermentation residues from biogas production as fertiliser for the cultivated biomass. The same applies to thermal or electrical energy from the synthesis processes: it replaces the corresponding energy in upstream processes such as electrolysis or CO_2 capture. Beyond this, no credits or debits (e.g., for fermentation residues from the fermentation of biogenic residues and waste materials) are allocated.
- Specific assumptions had to be made for the supply of CO_2 for the production of 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-chains) 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 listed for information purposes.
    - In processes that do not require CO_2 separation from the product mixture (e.g., flue gases, cement plant, direct air capture), the expenses for separating the CO_2 from the process waste gas or air as well as all subsequent treatment steps (cleaning, compression, ...) are attributed 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 in a power plant is primarily used to capture the CO_2 for long-term geological storage (CCS, Carbon Capture and Storage). The utilisation of a share of this CO_2 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 attributed to the PtX energy source.
    - Another special case is the use of CO_2 from biogas treatment. During the processing of biomethane, the CO_2 is separated from the raw biogas and released into the atmosphere, which indicates that it is waste. On the other hand, direct energetic use of the biogas is currently a common practice. Accordingly, a separation of the CO_2 would 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.

5.1.4 Impact categories and indicators

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

The following impact categories and indicators were selected for this study:

- 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 [1992] in g PO_4eq.
- Ozone depletion: Ozone depletion potential (ODP) according to WMO [2014] in g CFC-11eq.
- Particulate matter: Particulate matter < 10 µm (PM10) according to De Leeuw [2002] and WHO [2006] in g PM10eq.
- Cumulative raw material demand (CRD)
- Land use: Hemeroby concept according to Fehrenbach [2015] in m^2a
- Water consumption: Net water consumption (input minus output to the same water catchment area) in l H_2O

5.2 Screening LCAs and 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 were e.g., doubts about sustainably available biomass resources. However, there are many possible ways to combine the modules and create supply paths with a technical implementation potential and locations with significant availability.

Another criterion was that the set of selected paths should include both those paths with particularly low environmental impacts and disadvantageous paths with particularly high environmental impacts. However, considering the numerous process steps and their different characteristics, it is not straightforward to assess which variants (e.g., of the power source, electrolysis technology, synthesis or transport route) in a supply path may have a major or minor impact on the environmental impact. A selection based on expert estimates alone is not sufficient to eliminate this uncertainty.

5.2.1 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 performed. These assessments were carried out in two steps. In the first step, the technologies were grouped with respect 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. Additionally, the decrease of greenhouse gas emissions is one of the main motivations for the production of energy carriers based on electricity and/or biomass.

Table 6: Grouping of technology modules according to process steps

Electricity	Electrolysis	CO_2 source	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
PVground			Wood scrap		Biomethane
PVroof					
Geothermal energy					

WindON/OFF: Wind energy plants onshore/offshore, Water: Run-of-the-river power plants, CSP: Concentrating solar power plants, PVground/roof: Photovoltaic plants ground-mounted/roof, AEL: Alkaline electrolysis, PEM: PEM electrolysis, HTEL: High-temperature electrolysis, DAC: CO_2 capture from the air, SRC: short-rotation plantation (poplars), BtL: Synthesis based on biomass, PBtL: Synthesis based on electricity and biomass, PtL: Synthesis based on electricity, PtG: Synthesis of 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 6 shows the results of the LCA GWP analyses for the technology groups by means of the coloured background. Among the electricity generation options, hydropower plants have the lowest global warming potential per kilowatt-hour, while ground-mounted PV plants show the highest GWP. CO_2 capture from the air has a higher GWP than CO_2 capture from biogas due to its higher energy demand. Among the biomass sources for BtL synthesis, straw performs best and wood from short-rotation plantations performs worst. For biomass fermentation, maize carries the highest GHG loads and waste such as biowaste carries the lowest loads.

In a subsequent step, the modules with each the highest and lowest global warming potential were combined to form supply paths with particularly high and particularly low GWP, respectively (Table 7). These paths thus define a corridor.

Only the technical data determined for the reference year 2015 were included in the calculations for the screening LCAs. Production outside Germany was examined schematically by assuming a transport distance of 5000 kilometres for single variants. Other site parameters such as full-load hours of the power source were not considered at this point; the energetic interconnection of the modules (heat and electricity utilisation from the synthesis plant) was not taken into account either. The global warming potential of each PtL paths was calculated for both Fischer-Tropsch synthesis and methanol synthesis.

Table 7: List of supply paths for the screening LCA

Product	Location	Synthesis	CO_2 source	Biomass	Electricity	Electrolysis	Transport
Fischer-Tropsch	Germany	BtL	---	Straw	---	---	Truck
Methanol	Germany	BtL	---	Straw	---	---	Truck
Fischer-Tropsch	Germany	PBtL	---	Straw	Water	AEL	Truck
Methanol	Germany	PBtL	---	Straw	Water	AEL	Truck
Fischer-Tropsch	Germany	PtL	Biogas	---	Water	AEL	Truck
Methanol	Germany	PtL	Biogas	---	Water	AEL	Truck
SNG	Germany	PtG	Biogas	---	Water	AEL	Gas grid
Biomethane	Germany	Biogas	---	Bio-waste	---	---	Gas grid
Hydrogen	Germany	H_2	---	---	Water	AEL	Gas grid
Fischer-Tropsch	Abroad	PtL	Biogas	---	Water	AEL	HVDC + truck
Methanol	Abroad	PtL	Biogas	---	Water	AEL	HVDC + truck
Fischer-Tropsch	Abroad	PtL	Biogas	---	Water	AEL	Tanker + truck
Methanol	Abroad	PtL	Biogas	---	Water	AEL	Tanker + truck
SNG	Abroad	PtG	Biogas	---	Water	AEL	HVDC + gas grid
Biomethane	Abroad	SNG	Biogas	---	Water	AEL	Pipeline
Hydrogen	Abroad	SNG	Biogas	---	Water	AEL	Tanker + gas grid
Fischer-Tropsch	Germany	BtL	---	SRC	---	---	Truck
Methanol	Germany	BtL	---	SRC	---	---	Truck
Fischer-Tropsch	Germany	PBtL	---	SRC	PVground	AEL	Truck
Methanol	Germany	PBtL	---	SRC	PVground	AEL	Truck
Fischer-Tropsch	Germany	PtL	DAC	---	PVground	AEL	Truck

Product	Location	Synthesis	CO_2 source	Biomass	Electricity	Electrolysis	Transport
Methanol	Germany	PtL	DAC	---	PVground	AEL	Truck
SNG	Germany	SNG	DAC	---	PVground	AEL	Gas grid
Biomethane	Germany	Biogas	---	Maize/slurry	---	---	Gas grid

The paths that were combined from modules with low GWP are marked green.
The most favourable (green) paths in combination with transport from abroad are marked grey.
The paths that have been combined from modules with high GWP are marked in light brown.

Individual process steps with particularly large or small contributions to the overall GWP result could be identified using the results of screening LCA:

- For the supply paths in which electrolytic hydrogen is required for synthesis (PtL, PBtL), the provision of electricity for electrolysis contributes the largest part of the total GWP. At the same time, (renewable) electricity production exhibits a wide range of possible GWP contributions due to the loads involved in the production of the plants, which depend both on the type of electricity source and on the possible number of full-load hours at different locations. Therefore, a large variation of power sources and locations is useful for the final path selection.
- The GWP of biomass used in BtL and PBtL processes is another key factor for the overall result of a supply path. The greatest differences in GWP are evident between biogenic residues and cultivated biomass.
- The findings from the synthesis of methanol can be transferred to Fischer-Tropsch synthesis and vice versa for all synthesis processes. However, both products should always be calculated in the final paths since the actual environmental impacts of the products per unit of energy (MJ LHV) differ.
- The transport of liquid hydrocarbons over long distances is associated with significantly less environmental impacts than the equivalent electricity transport using high-voltage direct current transmission (HVDC). For comparison, only one path with HVDC transmission for Fischer-Tropsch fuel and methanol should be included in the final path selection.
- In contrast, ship transport of synthetic natural gas does not have a clear advantage over HVDC electricity transport due to high methane losses. Although the screening LCAs showed a clear advantage for transporting SNG by pipeline, but the construction of the pipeline was not included. Therefore, a comparison of different transport options for SNG from remote locations is considered useful.

5.2.2 List of selected supply paths

Based on the findings of the screening LCAs and in combination with the analysis of location factors in Chapter 4, a total of 62 supply paths were selected according to the following considerations:

- The paths of the screening LCAs were selected in order to include particularly favourable and unfavourable overall results. Therefore, it made sense to consider them also in the full LCA. 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 key environmental factor for many processes. It therefore made sense to consider several other types of electricity generation and locations. In Germany additionally wind onshore and offshore, in other countries wind onshore, CSP, and geothermal.
- To investigate the effects of transporting electricity or products from abroad, supply routes with Morocco and Saudi Arabia were selected, each with transport by HVDC/tanker/pipeline.
- To explore the potential of new electrolysis techniques, high-temperature electrolysis in combination with two FT-P(B)tL processes was selected along with PEM electrolysis in the best PtL path.
- Industrial and power plant CO_2 sources should be included in order 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, using electricity from the German electricity grid.
- Additionally, the cases of CO_2 capture from a waste incineration plant and an oxyfuel power plant for Fischer-Tropsch fuels are considered.
- Two additional paths with alternative purification/separation processes for biomethane were added.

The criteria for this selection are summarised in Table 8.

Table 8: Selection criteria for the final supply paths

Selection criterion	Path elements
Paths from the screening LCA were retained. Hydropower replaced by wind power	Straw and SRC as BtL biomass, organic waste/green cuttings and maize/slurry as biogas substrates, CO_2 from DAC and biogas processing, PVground and wind onshore as power source, AEL
Variations of 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
Further sources of CO_2	Cement industry, lignite power plant, oxyfuel power plant, waste incineration plant
Variation of biogas/biomethane treatment process	Amine scrubbing, pressure water scrubbing, membrane separation

All supply paths are shown in Table 9 to Table 13. The fact that the table provides 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, allowing to examine the influences of supply factors beyond transport and full-load hours of the power source. These influences are mapped and examined in a number of paths for foreign countries and can be transferred as a trend to other - not examined - supply paths.

Table 9: 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

Path No.	Location	Synthesis	CO_2 source	Biomass	Electricity	H_2	Transport
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 electricity mix	AEL	Truck

Table 10: 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 11: Supply paths 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 12: 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 13: Biomethane supply paths

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

Table 14: Additional supply paths for Fischer-Tropsch fuel

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

5.3 Results of the life cycle assessments

In this chapter, the results of the LCA calculations are presented first at the level of the individual products - Fischer-Tropsch fuel (Chapter 5.3.3.1), methanol (Chapter 5.3.3.2), synthetic natural gas (Chapter 5.3.3.3), biomethane (Chapter 5.3.3.4) and hydrogen (Chapter 5.3.3.5). In each case, the global warming potentials (GWPs) for the reference years 2015 and 2050 are discussed in detail. As the second main case the operation of the synthesis plants is considered at different full-load hours. The ranges of results and the dominant process steps are given for all impact categories. Individual results are highlighted wherever they provide special insights into a specific supply path, raw materials and fuels used or transport routes.

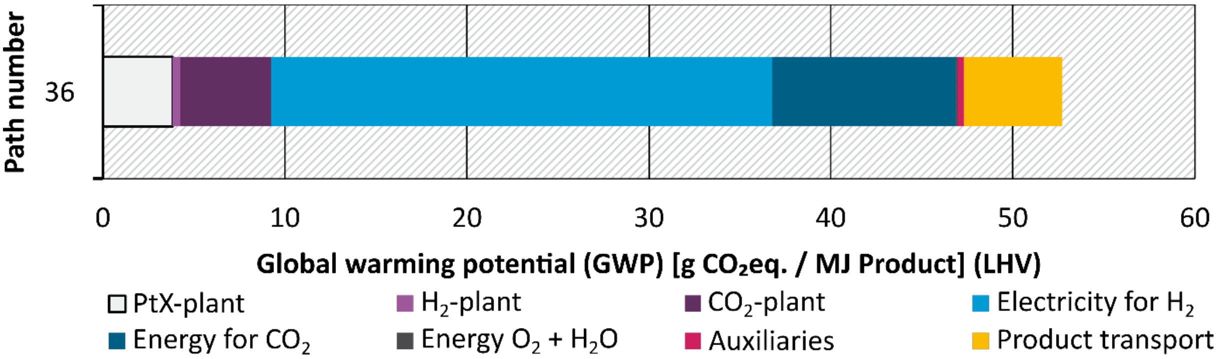
As throughout the report, the results for the reference year 2030 are not presented because they do not provide fundamentally different insights compared to the years 2015 and 2050, but only represent an intermediate step between them.

In the second part of the analysis (Chapter 5.3.4), the results for all products and impact categories are presented in their ranges, compared with each other, and related to the respective fossil reference values. The materials, methods and processes dominating the respective LCA results are identified.

5.3.1 Legend and reference products

The results of the calculations are presented as stacked bars, which are made up of the contributions of the individual process steps to the overall result. Figure 33 shows an example of the global warming potential of deployment path 36.

Figure 33: Exemplary diagram for the global warming potential



Source: own figure, ifeu

In this path, methanol is synthesised with electricity from a ground mounted PV plant in Morocco and CO_2 from the air. The finished product is then brought to Germany by tanker and transported by truck to its final destination, the centre of Germany. The activities considered in the individual process steps of this and all similar diagrams are listed in Table 15.

Table 15: Process step breakdown of LCA results

Process step	Activities considered
PtX plant	Construction and operation of the synthesis plant, also direct emissions (e.g., from residual gas combustion or gas cleaning)
H_2 plant	Construction and operation of the electrolysis plant, also direct emissions (from H_2 leaks). The electricity for the electrolysis is **not** accounted for here, but under electricity for H_2
CO_2 plant	Construction and operation of the CO_2 capture plant, also direct emissions (e.g., Emissions of the scrubbing solution). Heat and electricity for the separation is **not** accounted for here, but under Energy for CO_2
Biogas plant	Construction and operation of the biogas plant, also direct emissions.
Biomass cultivation/transport	Cultivating / harvesting / collecting, chopping, bundling and transporting of biomass to the synthesis plant
Electricity for H_2	Electricity for water electrolysis
Energy for CO_2	Heat and electricity for the capture of CO_2
Energy O_2+Water	Heat and electricity for the supply of oxygen for the gasification of biomass and for the supply of process and cooling water
Auxiliary materials	Production of auxiliary materials for use in the synthesis and separation plants (catalysts, scrubbing liquids, adsorber materials)
Power transmission HVDC	Construction of the high-voltage direct current line and transmission losses during electricity transmission
Transport products	Construction and operation of transport infrastructure and direct emissions from the transport of products (pipeline, tanker, gas liquefaction, gas grid, lorries)
CO_2 from oxyfuel	CO_2 captured from an oxyfuel power plant and therefore charged to the PtX energy source (see chapter 5.1.3.4)
Fossil CO_2 for information	CO_2 that is captured from a lignite-fired power plant or a cement works and remains with this source in the balance sheet. (see Chapter 5.1.3.4)

The results of the LCA calculations are presented in chapter 5.3.3 for Fischer-Tropsch fuels and methanol in path groups, which differ in whether biomass is used or not. The following terms are used:

- In **fully electricity-based** paths (PtL), the necessary hydrogen is obtained from electrolysis alone and the carbon comes from industrial waste gases or air.
- In **biomass-based** paths, hydrogen and carbon are obtained either exclusively (in BtL processes) or predominantly (in PBtL processes) from biomass. The electrolytically generated hydrogen additionally used in PBtL processes allows to make better use of biogenic carbon.

This distinction between electricity-based and biomass-based paths is also useful from an engineering point of view. The biomass-based processes have a different level of technological maturity, which is mainly due to open technical issues in the gasification/pyrolysis of the biomasses.

To be able to interpret all LCA results appropriately, not only the absolute values in the various impact categories are important, but also a comparison with the environmental impacts of the same products when they are based on fossil raw materials. Table 16 shows these fossil reference products and their environmental impacts. The data are from [JOULES 2017] and calculations based on EcoInvent 3.5 [Wernet 2016].

For all impact categories except global warming potential (GWP), the values given correspond to the environmental impacts of the provision (upstream) of the reference products. For the global warming potential, the emissions from complete combustion of the carbon contained in the product are also added (emission factors). This presentation is standard practice in reporting on national greenhouse gas emissions [UBA 2016].

Similarly, for the products considered in this study, the respective CO_2 emissions are added – and the uptake of CO_2 at the beginning of the supply path is counted negatively with the same value, as this is withdrawn from the atmosphere or the emission into it is initially prevented.

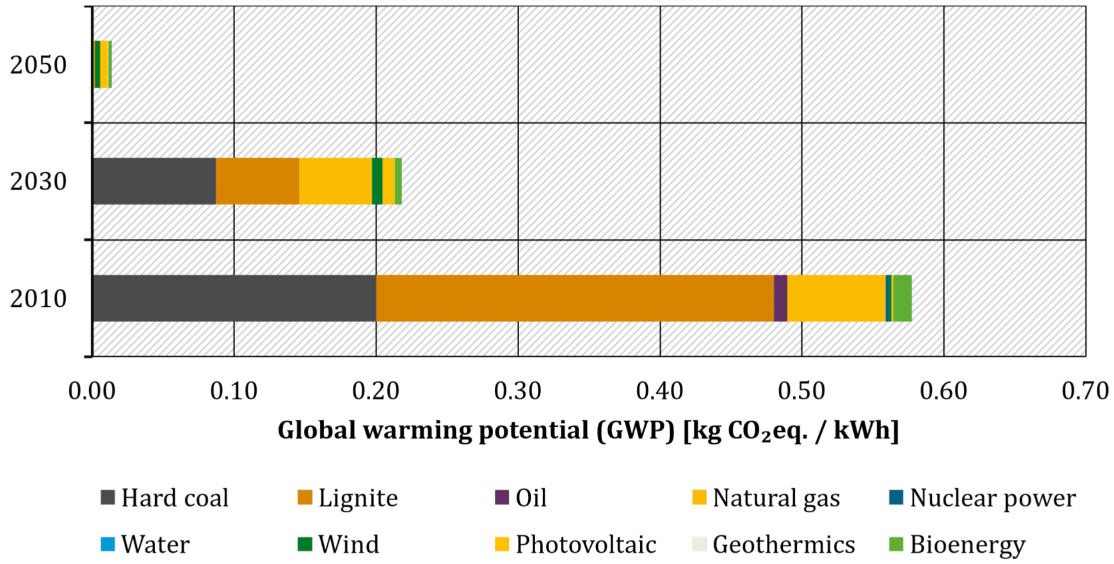
Table 16: Fossil reference products and their environmental impacts

Environmental Impact	Diesel	Petrol	Methanol from natural gas	Natural gas	Hydrogen from natural gas
Global warming potential g CO_2 eq/MJ	90	87	95	63	88
Acidification potential [g SO_2eq/MJ]	0.069	0.078	0.052	0.032	0.049
Eutrophication potential g PO_4eq/MJ].	0.021	0.021	0.0065	0.0015	0.0090
Cumulative energy demand [MJ/MJ]	1.3	1.2	1.6	1.01	1.4
Summer smog g C_2H_4eq/MJ	0.046	0.046	0.037	0.020	0.032
Ozone depletion [g CFC11eq/MJ]	6.4E-06	7.1-06	1.8E-05	1.1E-05	1.6E-05
Particulate matter [g/MJ]	0.062	0.068	0.047	0.022	0.042
Cumulative raw material demand [kg/MJ]	0.029	0.028	0.042	0.026	0.038
Land use [m^2a/MJ]	9.4E-05	9.4E-05	1.9E-04	5.4E-08	7.4E-08
Water demand [l/MJ]	0.068	0.065	0.048	1.1E-04	0.048

5.3.2 Global warming potential of the electricity mix

In the course of the transformation to a climate-neutral economy (Chapter 5.1.2), the greenhouse intensity of the German electricity mix is falling very sharply. On the one hand, fossil energy carriers are gradually being replaced by renewable ones, and on the other hand, greenhouse gas emissions from the manufacture of electricity generation plants are also falling. Improved processes, higher quotas of secondary materials and the use of renewable energies in the production of e.g., steel, cement and silicon are the reason for this (Chapter 5.1.2). The main potential of the German electricity mix will fall from 577 g CO_2eq/kWh in 2010 to 14 g CO_2eq/kWh in 2050 (Figure 34).

Figure 34: Global warming potential of the German electricity mix including upstream chains in 2010, 2030 and 2050



Source: own figure, ifeu

5.3.3 Analysis at product level

5.3.3.1 Fischer-Tropsch fuels

5.3.3.1.1 Brief overview, comments on data quality and technological maturity

Fischer-Tropsch synthesis based on CO_2 is a technology with the highest degree of maturity. During the reaction, a lot of heat is released which can be used in CO_2 capture or high-temperature electrolysis. Since a large part of the heat is generated at a high temperature level, electricity can also be generated from it and fed into the electrolysis. This energy integration in the process is assumed throughout the paths investigated here. This also applies to the (P)BtL paths, in which the excess heat is used to dry and pelletise the biomass. These assumptions reflect a rather optimistic view.

As a first main case, the maximum possible full load hours of the synthesis plants are calculated in all paths. The second main case is then the production with the full-load hours of the power source (explanations in Chapter 5.1.3.2)

The biomass-based processes ((P)BtL) have a different level of technological maturity than the fully electricity-based (PtL) processes. This is mainly due to still open technical questions regarding the gasification/pyrolysis of the biomasses and the integration of the electrolysers. Because of these technical differences between the PtL and (P)BtL paths, they will be considered separately.

5.3.3.1.2 Results for fully electricity-based paths

To make the following result diagrams better readable, the fully electricity-based supply paths for Fischer-Tropsch fuel are listed again in Table 17. Only the path numbers are then noted on the diagrams.

Table 17: Fully electricity-based supply paths for Fischer-Tropsch fuel

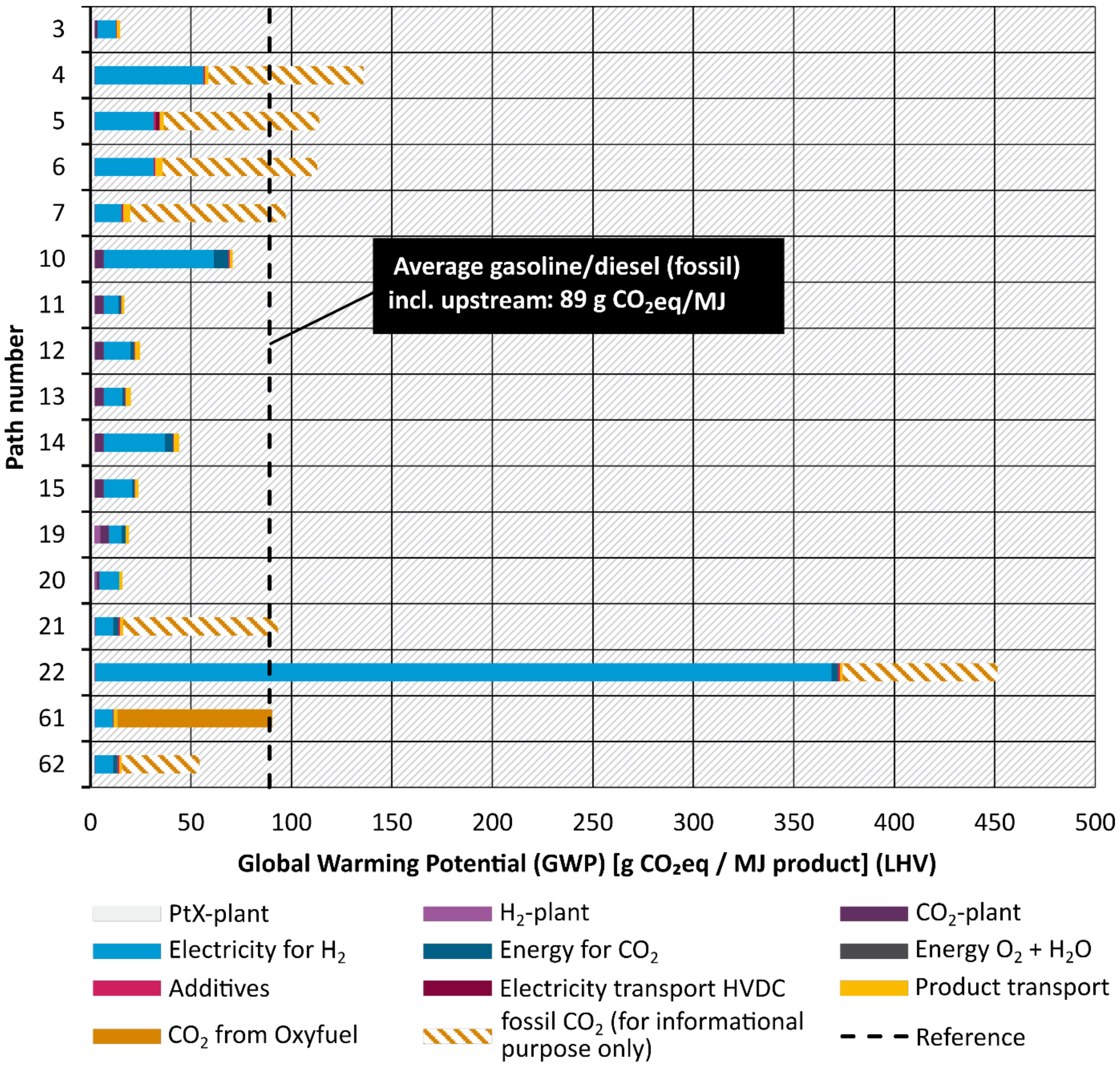
Path	Location	Synthesis	CO_2 source	Power source	Electrolysis	Transport
3	Germany	PtL	Biogas plant	Wind onshore	Alkaline electrolysis	Truck
4	Germany	PtL	Cement plant	PV ground	Alkaline electrolysis	Truck
5	Saudi Arabia	PtL in Germany	Cement plant in Germany	PV ground in Saudi Arabia	Alkaline electrolysis	High voltage direct current + truck
6	Saudi Arabia	PtL	Cement plant	PV ground	Alkaline electrolysis	Tanker + truck
7	Saudi Arabia	PtL	Cement plant	Solar power plant (CSP)	Alkaline electrolysis	Tanker + truck
10	Germany	PtL	DAC (air)	PV ground	Alkaline electrolysis	Truck
11	Germany	PtL	DAC (air)	Wind offshore	Alkaline electrolysis	Truck
12	Morocco	PtL	DAC (air)	Solar power plant (CSP)	Alkaline electrolysis	Tanker + truck
13	Morocco	PtL	DAC (air)	Wind onshore	Alkaline electrolysis	Tanker + truck
14	Morocco	PtL	DAC (air)	PV ground	Alkaline electrolysis	Tanker + truck
15	Iceland	PtL	DAC (air)	Geothermal power plant	Alkaline electrolysis	Tanker + truck
19	Germany	PtL	DAC (air)	Wind offshore	High Temperature Electrolysis	Truck
20	Germany	PtL	Biogas plant	Wind onshore	Polymer electrolyte membrane EL	Truck
21	Germany	PtL	Lignite power plant	Wind onshore	Alkaline electrolysis	Truck

Path	Location	Synthesis	CO_2 source	Power source	Electrolysis	Transport
22	Germany	PtL	Lignite power plant	Electricity mix	Alkaline electrolysis	Truck
61	Germany	PtL	Oxyfuel lignite power plant	Wind onshore	Alkaline electrolysis	Truck
62	Germany	PtL	Waste incineration plant	Wind onshore	Alkaline electrolysis	Truck

5.3.3.1.2.1 Global warming potential today

Figure 35 shows the results for the global warming potential (GWP) of the fully electricity-based Fischer-Tropsch paths (PtL synthesis) for the year 2015. The process steps broken down in the results are described in more detail in Table 15. Path 22, in which the electricity for electrolysis comes from the German electricity mix, clearly scores worst, which is due to the high proportion of fossil fuels in electricity generation. Also path 61 with CO_2 capture from an oxyfuel power plant exceeds the reference value of a current fossil fuel. If the CO_2 from cement and lignite-fired power plants were to be allocated to the fuel instead of just reporting it here for information, these paths would also perform worse than the conventional reference.

Figure 35: Global warming potential 2015 of fully electricity-based Fischer-Tropsch paths (full load hours synthesis plant)

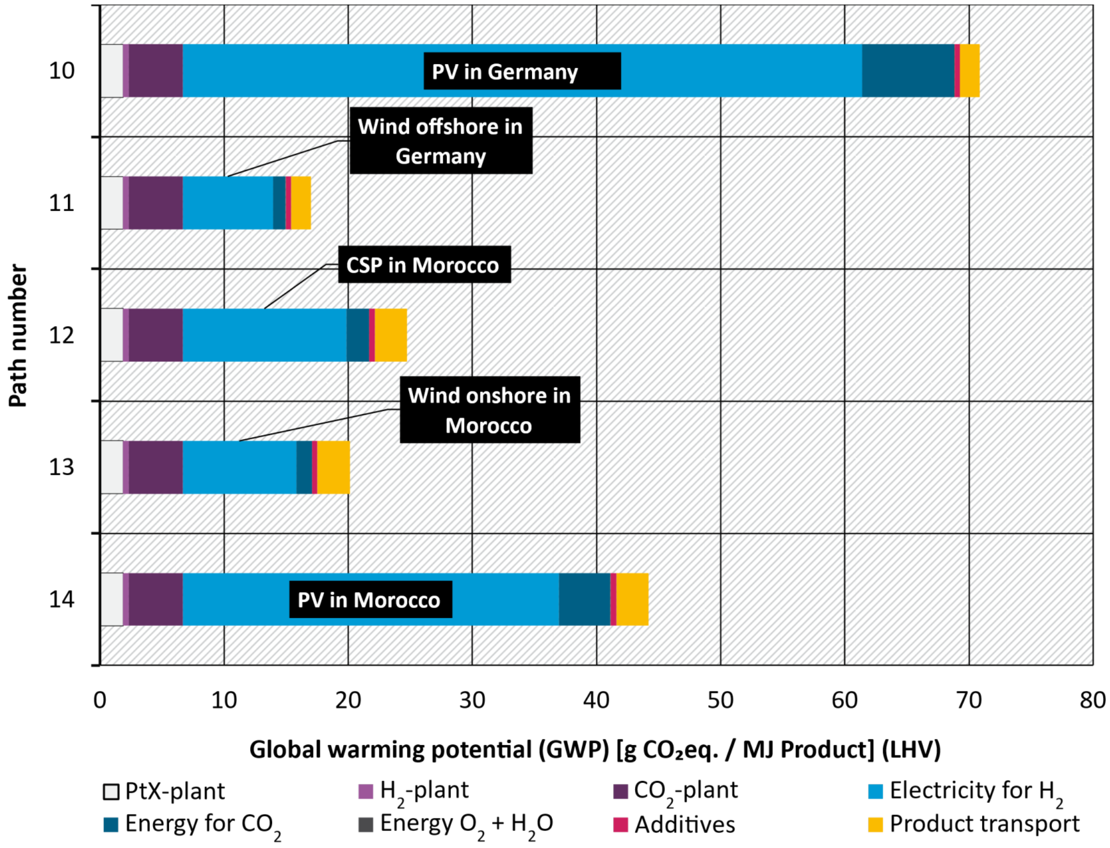


Source: own figure, ifeu

In all paths, except oxyfuel path 61, the electricity for electrolysis represents the largest share of the global warming potential. Paths 10 to 19 also reflect the high expenditure on equipment for CO_2 capture from the air. The H_2 plant only makes a noteworthy contribution in path 19 because high-temperature electrolysis is used there, which still has a relatively short service life. The paths with a capture of CO_2 from biogas plants (3, 20) perform best. Several paths lie in the range from 20 to 25 g CO_2eq/MJ product, which means a reduction of about 75% compared to conventional fuel.

The extent to which the electricity source used and its location-dependent full-load hours determine the global warming potential is shown in Figure 36. For the paths 10 to 14 shown there, wind on- and offshore, open-ground PV systems and concentrating solar power are used as power sources, and they all contain a capture of CO_2 from the air. They are located in both Germany and Morocco.

Figure 36: Influence of the electricity source and its annual full-load hours on the global warming potential of 2015 of electricity-based Fischer-Tropsch paths (full load hours synthesis plant)



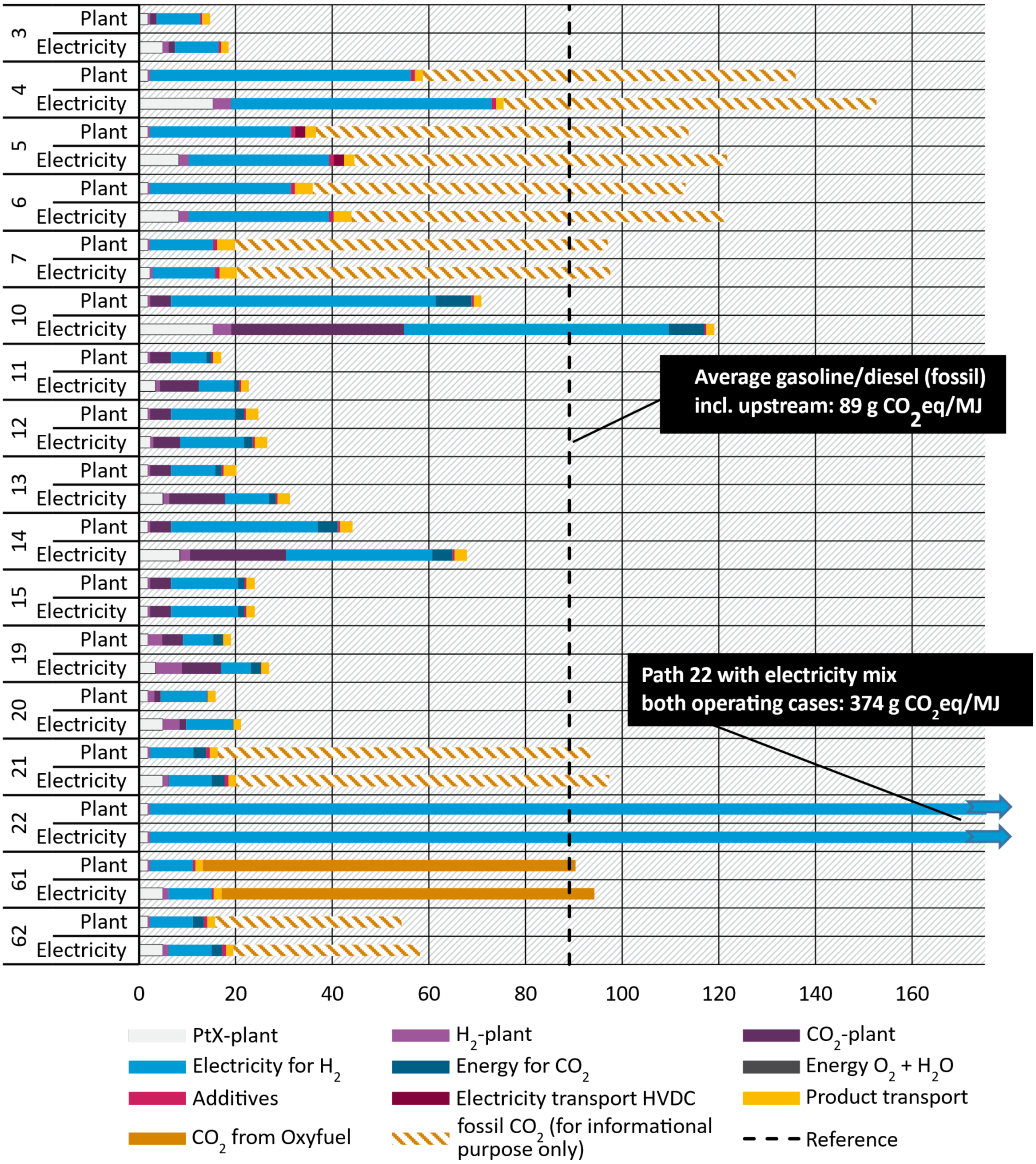
Source: own figure, ifeu

Electricity from photovoltaic systems has a higher global warming potential per kilowatt hour compared to wind energy systems. This is particularly true at locations such as Germany with relatively low annual full-load hours, where less electricity is generated over the entire service life than at sunny locations. But even in Morocco, electricity generation with photovoltaics performs even worse than with wind power at the same location or in Germany. Since CO_2 capture from the air is energy-intensive and cannot be completely supplied from the waste heat of the Fischer-Tropsch synthesis in the reference year 2015, its contribution also scales with the power source used and its full-load hours. Added to this is the relatively high cost of the CO_2 plant itself. The transport of the liquid energy carriers, on the other hand, plays a minor role.

5.3.3.1.2.2 Second main case: global warming potential today depending on the mode of operation

As a second main case, the global warming potential of the electricity-based Fischer-Tropsch paths 2015 was calculated using the full load hours of the electricity source. This approximates the case where the synthesis plant only runs when electricity is available from the linked power source (see Chapter 5.1.3.2). Figure 37 shows the results of these LCA calculations in comparison with the "full-load hours synthesis plant" mode of operation.

Figure 37: Global warming potential 2015 of fully electricity-based Fischer-Tropsch paths (full load hours synthesis plant and full load hours power source)



Source: own figure, ifeu

In almost all paths, the global warming potential increases compared to the calculation with the full load hours of the synthesis plant, especially for electricity sources with low full load hours. The reason for this is the higher contribution of the plant infrastructure. The environmental impacts arising from the construction of these plants are distributed over a lower product output at lower full-load hours and the same lifetime. For path 10 (CO_2 capture from the air, power source: PV in Germany), the change in operating case leads to an increase of 68%. With 119 g CO_2eq/MJ, this path is then significantly higher than the fossil reference.

5.3.3.1.2.3 Global warming potential 2050

Figure 38 compares the results for the global warming potential (GWP) of the fully electricity-based Fischer-Tropsch paths (PtL synthesis) for the year 2050 with those for 2015. In 2050, most of the paths are in the range of 10 to 15 g CO_2eq/MJ product, which means a reduction of about 85% compared to conventional fuel. The fact that the global warming potential is not even lower is due to the emissions still existing in the upstream processes[12].

Compared to the results for 2015, the values have fallen by 7 to 95%. The smallest improvement is seen in path 61, where the CO_2 removed from the oxyfuel power plant continues to be fully counted. The biggest decrease is in path 22, where the electricity for electrolysis is taken from the German electricity mix.

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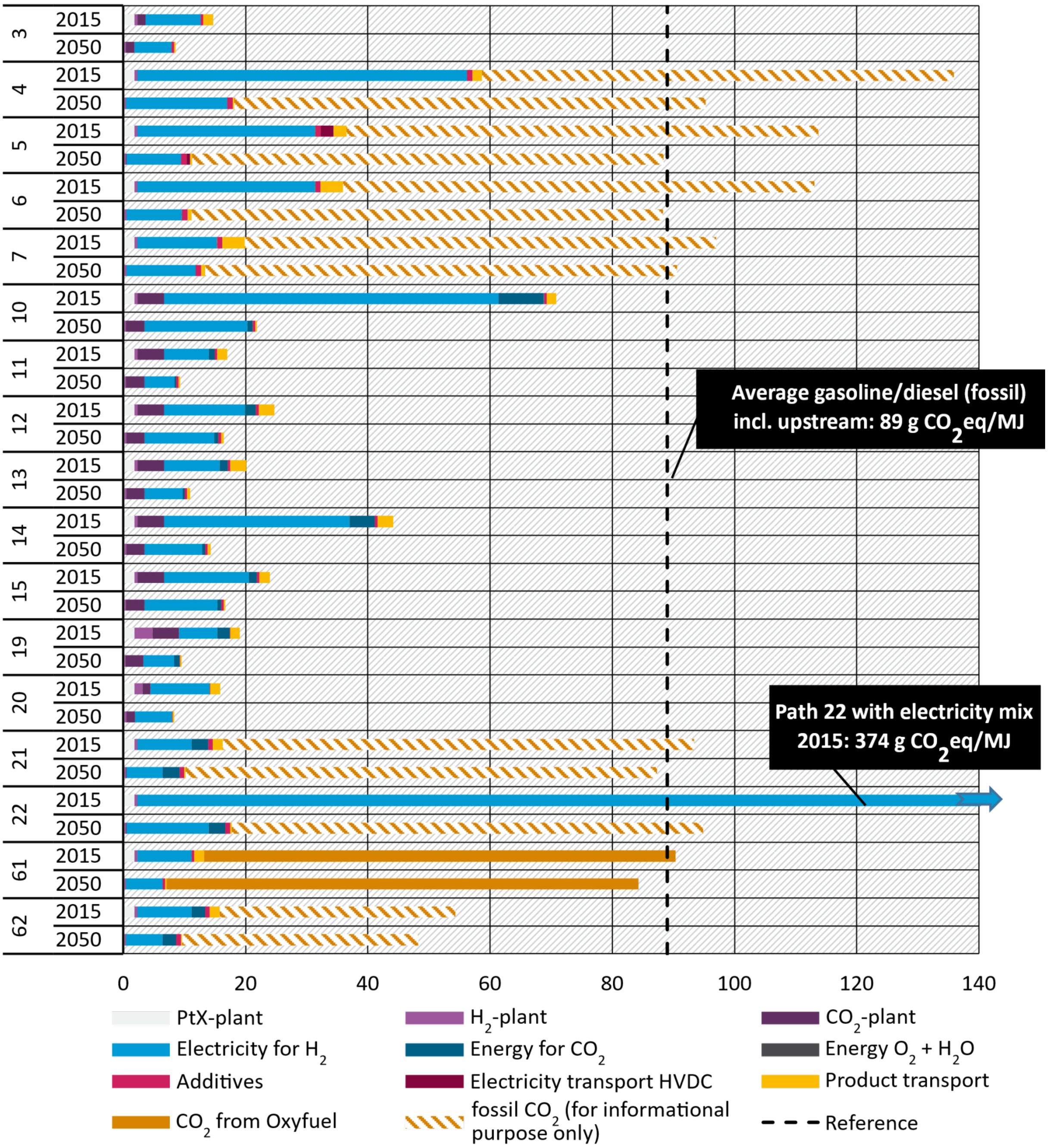
[12] As in the RESCUE study, it is assumed that the world outside Europe is also undergoing a transformation towards greenhouse gas neutrality but with a delay of 10 years.

Figure 38: **Global warming potential in 2050 and 2015 of fully electricity-based Fischer-Tropsch paths (full load hours synthesis plant)**



Source: own figure, ifeu

The decrease for other paths is also due to the decreasing global warming potential of electricity sources, in particular wind power and photovoltaics. The global warming potential for paths with photovoltaic (4, 5, 6, 10, 14) as a source decreases by around 70%, and by 40 to 50% for paths with wind power (11, 19, 3, 62, 20, 21, 13). The paths with concentrated solar power and geothermal energy (7, 12, 15) improve by just over 30%. The improved production of the synthesis plants also contributes, albeit small, to this positive development. In addition, Fischer-Tropsch fuel will be transported by tankers and trucks in 2050, which in turn will be powered by this fuel.

5.3.3.1.2.4 *Selected results in other impact categories*

Table 18 shows the ranges of results for all ten environmental impacts examined in this study for the fully electricity-based Fischer-Tropsch paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the website of the Federal Environment Agency. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts can be found in chapter 5.3.4 on cross-product analysis.

Table 18: Ranges of LCA results 2050 of fully electricity-based Fischer-Tropsch paths (full-load hours synthesis plant)

Environmental Impact	Reference (average value diesel/petrol)	Min (path)	Max (path)	Comment
Global warming potential [g CO_2 eq/MJ]	89	8.3 (20)	84 (61)	Most paths are between 8 and 20 g CO_2 eq/MJ
Acidification [g SO_2eq/MJ]	0.074	0.076 (19)	5.1 (15)	Path 15 with singularly high value. The others are below 0.315 g SO_2eq/MJ
Eutrophication g PO_4eq/MJ].	0.021	0.012 (15)	0.096 (22)	
Cumulative energy demand [MJ/MJ]	1.2	1.9 (7)	5.4 (15)	Path 15 with singularly high value Most others are between 1.9 and 2.4 MJ/MJ
Summer smog g C_2H_4eq/MJ	0.046	0.014 (15)	0.065 (10)	
Ozone depletion [g CFC11eq/MJ]	6.4E-06	8.6E-06 (61)	3.1E-04 (12)	
Particulate matter [g/MJ]	0.065	0.050 (15)	0.19 (22)	
Cumulative raw material demand [kg/MJ]	0.029	0.015 (15)	0.066 (10)	Path 15 with singularly low value. Most others are between 0.030 and 0.065 kg/MJ
Land use [m^2a/MJ]	9.4E-05	6.7E-03 (61)	2.3E-02 (10)	
Water demand [l/MJ]	0.067	0.12 (13)	2.4 (15)	Path 15 with singularly high value Most others are between 0.18 and 0.45 l/MJ

As described in Chapter 5.3.3.1.2.3 the values for **global warming potential** are between 8 and 84 g CO_2 eq/MJ. This corresponds to 9 and 94% of the fossil reference (the average global warming potential of diesel and petrol, including upstream). Paths 20 and 61 are the ones with the lowest and highest emissions. Most paths are between 8 and 20 g CO_2 eq/MJ. The main source is electricity generation for electrolysis.

For **acidification,** the values are between 0.076 and 5.1 g SO_2eq/MJ. This corresponds to 103 and 6,900% of the fossil reference. Paths 19 and 15 are the ones with the lowest and highest emissions. Most paths are below 0.32 g SO_2eq/MJ. The main source is electricity generation for electrolysis – in an extreme way the direct emissions from the geothermal power plant in path 15.

The values for **eutrophication** are between 0.012 and 0.096 g PO_4eq/MJ. This corresponds to 57 and 457% of the fossil reference. Paths 15 and 22 are the ones with the lowest and highest emissions. Many paths are around 0.040 g PO_4eq/MJ. The main source is electricity generation for electrolysis and lignite for capture energy from the lignite-fired power plant.

The **cumulative energy demand** is between 1.87 and 5.36 MJ/MJ. This corresponds to 152 and 436% of the fossil reference. Paths 7 and 15 are the ones with the lowest and highest emissions. Many paths are between 1.9 and 2.4 MJ/MJ. The main cause is electricity generation for electrolysis.

For the impact category **summer smog,** the values lie between 0.014 and 0.065 g C_2H_4eq/MJ. This corresponds to 30 and 140% of the fossil reference. Paths 15 and 10 are the ones with the lowest and highest emissions. Many paths are around 0.040 g C_2H_4eq/MJ. The main source is electricity generation for the electrolysis, but the construction of the plants and lignite for the capture energy from the lignite-fired power plant also play a role.

The values for **ozone depletion** range from 8.6E-06 to 3.1E-04 g CFC11 eq/MJ. This is between 140 and 4,800% of the fossil reference. Paths 61 and 12 are the ones with the lowest and highest emissions. Many paths are around 4.0E-06 g CFC11 eq/MJ. The main source is electricity generation in CSP power plants and the construction of facilities for the capture of CO_2 from the air.

For the impact category **particulate matter,** the values are between 0.05 and 0.19 g/MJ. This corresponds to 77 and 290% of the fossil reference. Paths 15 and 22 are the ones with the lowest and highest emissions. Many paths are around 0.10 g/MJ or below. The main source is electricity generation for electrolysis and the construction of the plants.

The **cumulative raw material demand** is between 0.015 and 0.066 kg/MJ. This corresponds to 52 and 224% of the fossil reference. Paths 15 and 10 are the ones with the lowest and highest emissions. Many paths are between 0.040 and 0.050 kg/MJ. The main cause is electricity generation for electrolysis.

The values for **land use** are between 6.7E-03 and 2.3E-02 $m^2a/$MJ. This corresponds to 7,100 and 25,000% of the fossil reference. Paths 61 and 10 are the ones with the least and most impact. The main source is electricity generation for electrolysis, especially from photovoltaic systems.

The **water use** is between 0.12 and 2.4 l/MJ. This corresponds to 175 and 3,600% of the fossil reference. Trails 13 and 15 are the ones with the lowest and highest emissions. Many paths are around 0.300 l/MJ. The main cause is the generation of electricity for electrolysis – in an extreme way in the geothermal power plant in path 15.

5.3.3.1.3 Results for biomass-based paths

To make the following result diagrams more readable, the biomass-based supply paths for Fischer-Tropsch fuel are listed again in Table 19. Only the path numbers are then noted on the diagrams.

Table 19: Biomass-based supply paths for Fischer-Tropsch fuel

Path	Location	Synthesis	Biomass	Power source	Electrolysis	Transport
1	Germany	BtL	Straw	---	---	Truck
8	Germany	BtL	Poplar wood from Short rotation coppices	---	---	Truck
2	Germany	PBtL	Straw	Wind onshore	Alkaline electrolysis	Truck
9	Germany	PBtL	Poplar wood from Short rotation coppices	PV ground	Alkaline electrolysis	Truck
16	Sweden	PBtL	Forest residue wood	Hydropower	Alkaline electrolysis	Tanker + truck
17	Sweden	PBtL	Poplar wood from Short rotation coppices	Hydropower	Alkaline electrolysis	Tanker + truck
18	Germany	PBtL	Poplar wood from Short rotation coppices	Wind offshore	High Temperature EL	Truck

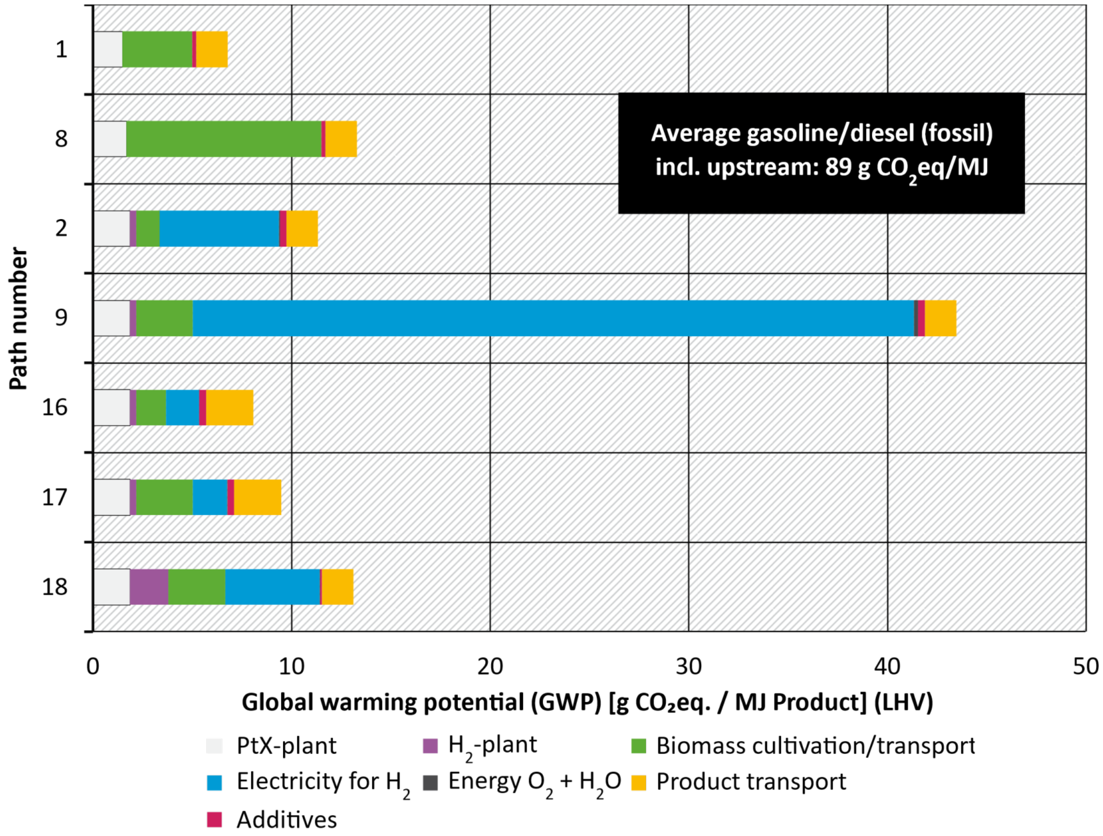
5.3.3.1.3.1 Global warming potential today

Figure 39 shows the results for the global warming potential (GWP) of the biomass-based Fischer-Tropsch paths ((P)BtL synthesis) for the year 2015. The process steps broken down in the results are described in more detail in Table 15. In the case of the paths that do not use hydrogen (1, 8), biomass cultivation and transport account for the largest share of the GWP. The larger value for path 8 reflects the higher emissions from the cultivation and harvesting of poplar wood from short-rotation plantations. Paths 2 and 9 use the same substrates as paths 1 and 8 (straw and poplar wood) but make better use of them by adding hydrogen. Therefore, the contribution of biomass in these paths is lower. On the other hand, this adds the global warming potential of the electricity for electrolysis, which in this case comes from photovoltaic systems.

Path 17 and 18 combine the efficient use of poplar wood biomass with low GWP electricity sources. This results in the overall low GWP. In path 18, the still short-lived high-temperature electrolysis makes a slightly higher contribution.

Most paths are in the range of 10 g CO_2eq/MJ product, which means a reduction of about 90% compared to conventional fuel. Only path 9, with 44 g CO_2eq/MJ product, achieves a reduction of 50% compared to the fossil reference.

Figure 39: Global warming potential 2015 of biomass-based Fischer-Tropsch paths (full load hours synthesis plant)



Source: own figure, ifeu

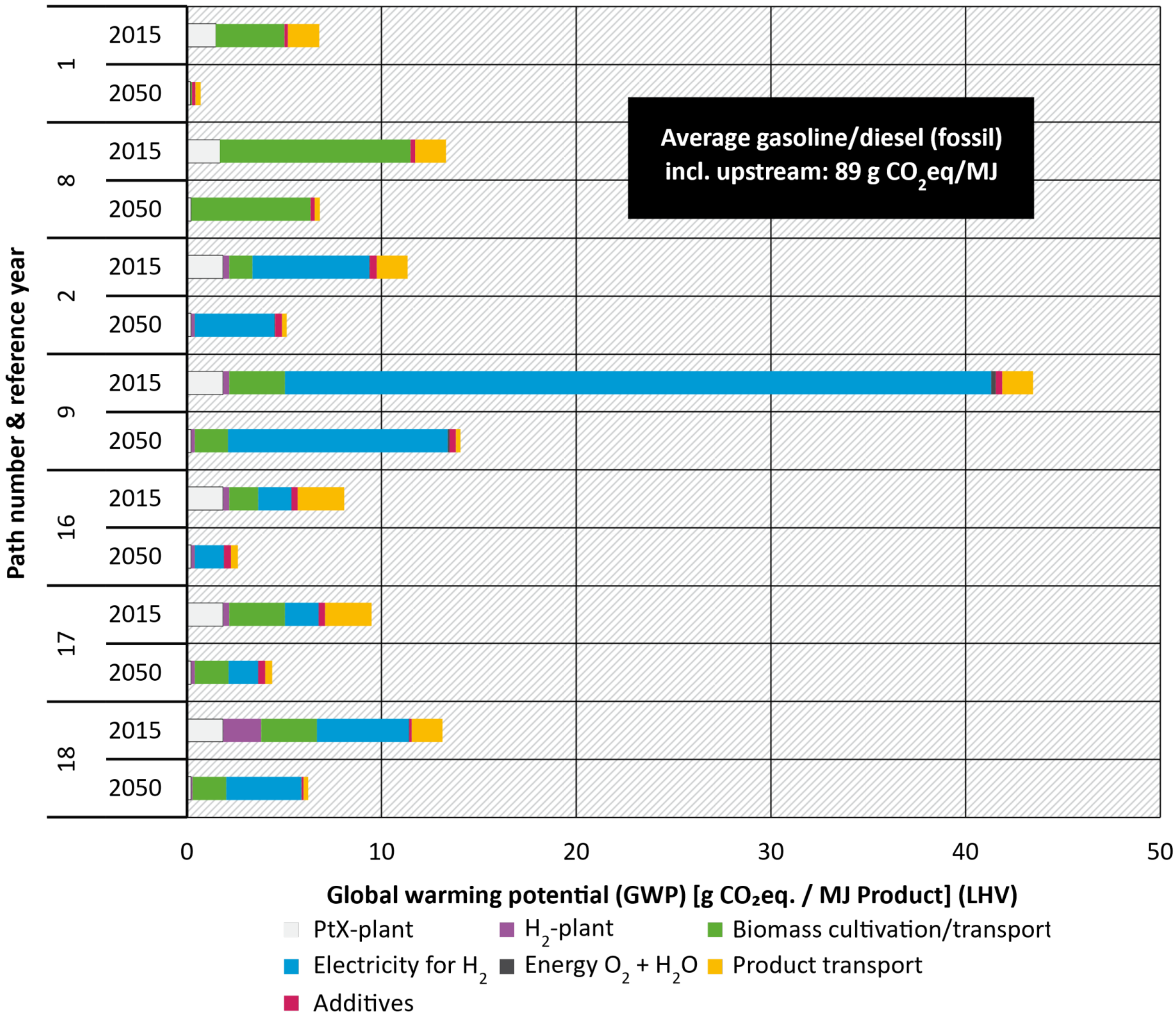
In the case of the Fischer-Tropsch paths, which are biomass-based, it does not make sense to present a second main case with the full load hours of the power source. These plants obtain most of the energy, carbon, and hydrogen for the synthesis from the biomass used, while the electricity only provides additional hydrogen for better utilisation of the carbon. This is either produced and stored in stock, or the plant is operated with the electricity mix in times of lack of electricity supply from renewable energy carriers.

5.3.3.1.3.2 Global warming potential 2050

Figure 40 compares the results for the global warming potential (GWP) of the Fischer-Tropsch paths ((P)BtL synthesis) for the year 2050, which are predominantly based on biomass, with those for 2015. Compared with the results for 2015, the values have fallen by 50 to 90%. The relatively sharpest decrease of 90% is in path 1, because the straw used there will be processed and transported by machines powered by Fischer-Tropsch fuels in 2050. Transport and processing are also improving for the other paths. For the cultivated biomass poplar wood, the GWP of biomass supply is thus reduced by about 40%. The global warming potential of electricity for electrolysis makes a proportionately higher contribution to overall results in 2050 than in 2015, even if the absolute values fall by around 20 to 30%.

Most paths are in the range of 5 g CO_2eq/MJ product in 2050, which means a reduction of about 94% compared to conventional fuel. Only path 9 achieves an 85% reduction compared to the fossil reference with 14 g CO_2eq/MJ product.

Figure 40: Global warming potential of biomass-based Fischer-Tropsch paths in 2050 and 2015 (full load hours synthesis plant)

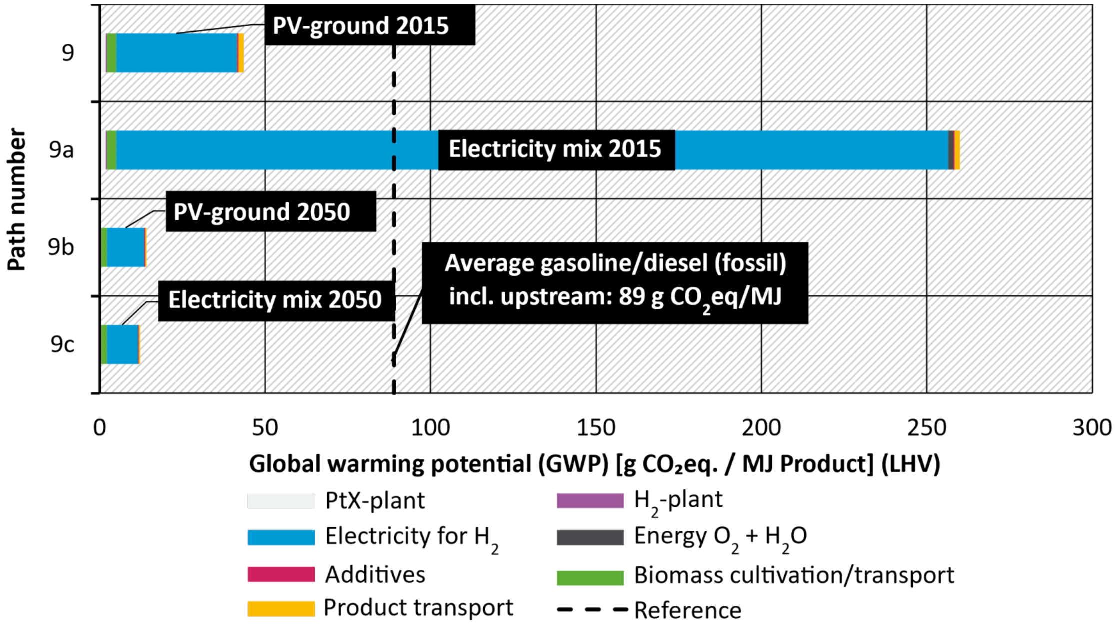


Source: own figure, ifeu

5.3.3.1.3.3 Sensitivities: global warming potential when operated with electricity mix

As sensitivities, the global warming potential of the biomass-based Fischer-Tropsch path 9 (FT-PBtL SRC, PV ground) is calculated with electricity procurement from the electricity mixes of the years 2015 and 2050. This represents the case where the synthesis plant continues to operate when electricity from the linked electricity source is not available. Figure 41 shows the results of these LCA calculations.

Figure 41: Sensitivity path 9 (FT-PBtL SRC) with PV electricity and electricity mix 2015/2050 (full load hours synthesis plant)



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For the year 2015, the electricity purchased from the electricity mix (path 9a) means an increase in global warming potential for path 9 from 43 to 260 g CO_2eq/MJ product. This is almost three times the reference value for fossil fuel. For the year 2050, the purchase of electricity from the mix (path 9c, 12 g CO_2eq/MJ product) is even an advantage over the pure use of photovoltaics (path 9b, 14 g CO_2eq/MJ product), as envisaged in path 9. This is because the electricity mix also includes other renewable sources with a lower global warming potential.

5.3.3.1.3.4 Selected results in other impact categories

In Table 20 the ranges of the results for all ten environmental impacts examined in this study for the biomass-based Fischer-Tropsch paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the Federal Environment Agency's website. A more detailed description of the causes (materials, procedures, processes) of the environmental impacts can be found in Chapter 5.3.4 on cross-product analysis.

Table 20: Ranges of LCA results in 2050 mainly biomass-based Fischer-Tropsch paths (full-load hours synthesis plant)

Environmental Impact	Reference (average value diesel/petrol)	Min (path)	Max (path)	Comment
Global warming potential [g CO_2eq/MJ]	89	0.69 (1)	14 (9)	Most paths are between 3 and 6 g CO_2eq/MJ
Acidification [g SO_2eq/MJ]	0.074	0.025 (1)	0.67 (8)	Most paths are below 0.300 g SO_2eq/MJ
Eutrophication g PO_4eq/MJ].	0.021	0.0028 (1)	0.13 (8)	Only paths 1 and 16 are below the fossil reference of 0.021 g PO_4eq/MJ
Cumulative energy demand [MJ/MJ]	1.2	2.2 (2)	3.4 (8)	Many paths are between 2.3 and 2.5 MJ/MJ
Summer smog [g C_2H_4eq/MJ	0.046	0.0066 (1)	0.041 (9)	Many paths are around 13 mg C_2H_4eq/MJ.
Ozone depletion [g CFC11eq/MJ]	6.4E-06	4.7E-06 (16)	3.7E-04 (8)s	Only the paths with residual biomass (1, 2, 16) are below the fossil reference
Particulate matter [g/MJ]	0.065	0.019 (1)	0.24 (8)	Only the paths with residual biomass (1, 2, 16) are below the fossil reference
Cumulative raw material demand [kg/MJ]	0.029	0.0039 (1)	0.041 (9)	Many paths are below 0.017 kg/MJ.
Land use [m^2a/MJ]	9.4E-0 5	1.0E-04 (1)	4.1E-02 (8)	Very large differences between residual and cultivated biomass
Water demand [l/MJ]	0.067	0.33 (16)	18 (8)	Very large differences between residual and cultivated biomass

As described in Chapter 5.3.3.1.3.2 the values for **global warming potential** are between 0.69 and 14 g CO_2eq/MJ. This corresponds to 1 and 16% of the fossil reference (the average global warming potential of diesel and petrol, including upstream). Paths 1 and 9 are the ones with the lowest and highest emissions. Most paths are between 3 and 6 g CO_2eq/MJ. The main sources are electricity generation for electrolysis and the cultivation of wood from short rotation coppices.

For **acidification,** the values are between 0.025 and 0.67 g SO_2eq/MJ. This corresponds to 34 and 900% of the fossil reference. Paths 1 and 8 are the ones with the lowest and highest emissions. Most paths are below 0.300 g SO_2eq/MJ, three below the fossil reference of 0.074 g SO_2eq/MJ. The main source is the cultivation of wood from short rotation coppices.

The values for **eutrophication** are between 0.0028 and 0.13 g PO_4eq/MJ. This is between 13 and 620% of the fossil reference. Paths 1 and 8 are the ones with the lowest and highest emissions. Only two paths (1 and 16) are below the fossil reference of 0.021 g PO_4eq/MJ. The main sources are electricity generation for electrolysis and the cultivation of wood from short rotation coppices.

The **cumulative energy demand** is between 2.2 and 3.4 MJ/MJ. This corresponds to 179 and 276% of the fossil reference. Paths 2 and 8 are the least and most energy intensive. Many paths lie between 2.3 and 2.5 MJ/MJ. The main causes are electricity generation for electrolysis and the cultivation and transport of biomass.

For the impact category **summer smog,** the values lie between 0.0066 and 0.041 g C_2H_4eq/MJ. This corresponds to 15 and 91% of the fossil reference. Paths 1 and 9 are the ones with the lowest and highest emissions. Many paths are around 13 mg C_2H_4eq/MJ. The main sources are electricity generation for electrolysis and cultivation and transport of the biomass.

For **ozone depletion,** the values are between 4.7E-06 and 3.7E-04 g CFC11eq/MJ. This is 76 and 5,900% of the fossil reference. Paths 16 and 8 are the ones with the lowest and highest emissions. Only the paths with residual biomass (1, 2, 16) are below the fossil reference of 6.15E-06 g CFC11 eq/MJ. The main source is the cultivation of wood from short rotation coppices.

The values for the impact category **particulate matter** are between 0.019 and 0.24 g/MJ. This corresponds to 29 and 370% of the fossil reference. Paths 1 and 8 are the ones with the lowest and highest emissions. Only the paths with residual biomass (1, 2, 16) are below the fossil reference of 0.065 g/MJ or below. The main sources are electricity generation for electrolysis and biomass cultivation.

Cumulative raw material demand ranges from 0.0039 to 0.041 kg/MJ. This corresponds to 14 and 166% of the fossil reference. Paths 1 and 9 are the ones with least and most demand. Many paths are below 0.017 kg/MJ. The main cause is electricity generation for electrolysis.

The values for the **land use** are between 1.0E-04 and 4.1E-02 m^2a/MJ. This corresponds to 110 and more than 44,000% of the fossil reference. Paths 1 and 8 are the ones with the least and most impacts. The main sources are the cultivation of wood from short rotation coppices and the generation of electricity for electrolysis, in particular from photovoltaic systems.

The **water demand** is between 0.33 and 18 l/MJ. This corresponds to 490 and 27,000% of the fossil reference. Trails 16 and 8 are the ones with the lowest and highest demand. The PBtL paths with wood from short rotation coppices are around 5 l/MJ, and the PBtL paths with residues are around 0.4 l/MJ. The main reason for this is the cultivation of wood from short rotation coppices.

5.3.3.2 Methanol

5.3.3.2.1 Brief overview, comments on data quality and technological maturity

Methanol synthesis based on CO_2 is a technology with a high degree of maturity. During the reaction a lot of heat is released, but some of this heat is used within the plant to purify the methanol. Therefore, this process does not have quite as much excess heat available as the Fischer-Tropsch synthesis, which can be used in CO_2 capture or high-temperature electrolysis. Since a large part of the heat is generated at a high temperature level, electricity can also be generated from it and fed into the electrolysis. This energy integration is assumed throughout the paths investigated here. This also applies to the (P)BtL paths, in which the excess heat is used to dry and pelletise the biomass.

As a base case, the maximum possible full-load hours of the synthesis plants are calculated in all paths. The second main case is then considered to be production with the full load hours of the power source (explanations in Chapter 5.1.3.2)

The biomass-based processes ((P)BtL), for example, have a different level of technological maturity than the fully electricity-based (PtL) processes. This is mainly due to still open technical questions regarding the gasification/pyrolysis of the biomasses and the integration of the electrolysers. Because of these technical differences between the PtL and (P)BtL paths, they will be considered separately below.

Production data for the manufacture of methanol were derived from thermodynamic process calculations with the software tool AspenPlus®. A high degree of heat integration was assumed. The data thus possibly reflect a rather optimistic view.

5.3.3.2.2 Results for fully electricity-based paths

To make the following result diagrams more readable, the fully electricity-based supply paths for Fischer-Tropsch fuel are listed again in Table 21. Only the path numbers are then noted on the diagrams.

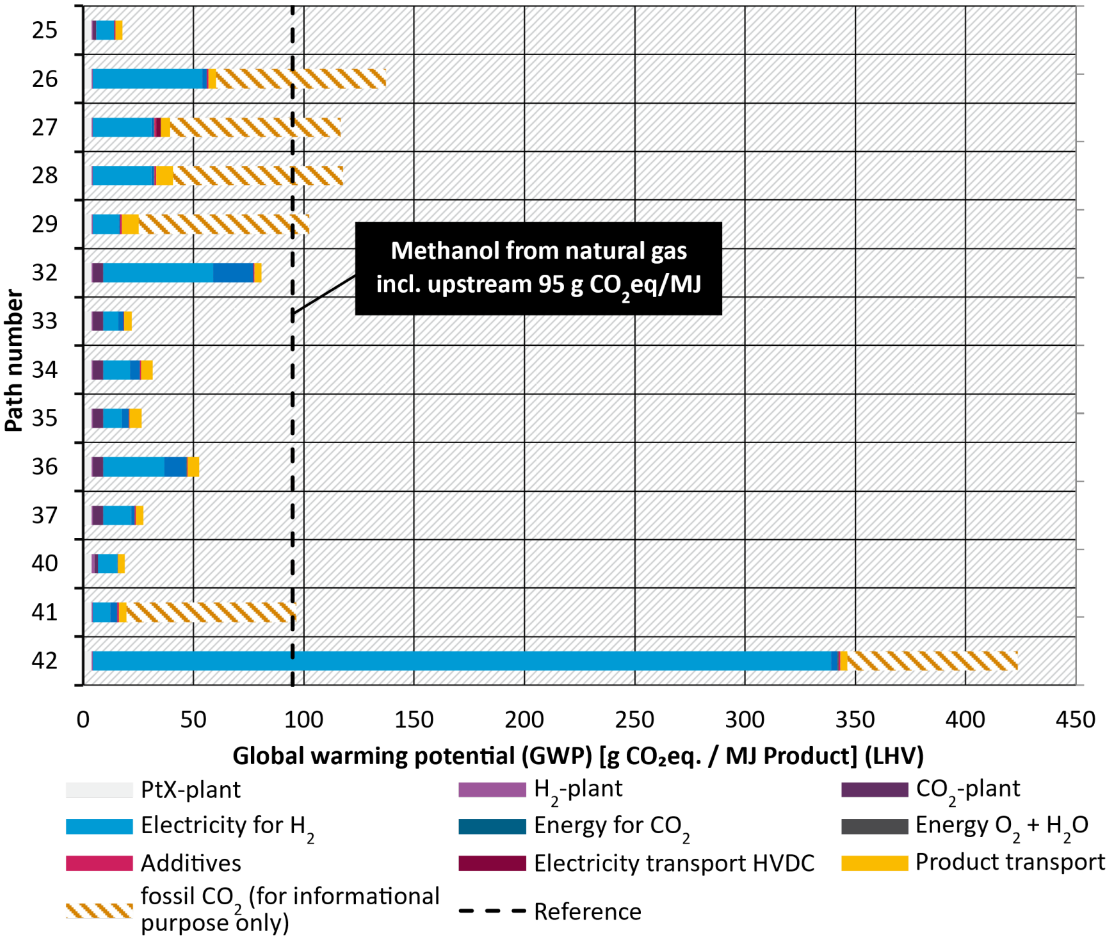
Table 21: **Fully electricity-based methanol supply paths**

Path	Location	Synthesis	CO_2 source	Power source	Electrolysis	Transport
25	Germany	PtL	Biogas plant	Wind onshore	Alkaline electrolysis	Truck
26	Germany	PtL	Cement plant	PVground	Alkaline electrolysis	Truck
27	Saudi Arabia	PtL in Germany	Cement plant in Germany	PVground in Saudi Arabia	Alkaline electrolysis	HVDC + truck
28	Saudi Arabia	PtL	Cement plant	PVground	Alkaline electrolysis	Tanker + truck
29	Saudi Arabia	PtL	Cement plant	Solar power plant (CSP)	Alkaline electrolysis	Tanker + truck
32	Germany	PtL	DAC (air)	PVground	Alkaline electrolysis	Truck
33	Germany	PtL	DAC (air)	Wind offshore	Alkaline electrolysis	Truck
34	Morocco	PtL	DAC (air)	Solar power plant (CSP)	Alkaline electrolysis	Tanker + truck
35	Morocco	PtL	DAC (air)	Wind onshore	Alkaline electrolysis	Tanker + truck
36	Morocco	PtL	DAC (air)	PVground	Alkaline electrolysis	Tanker + truck
37	Iceland	PtL	DAC (air)	Geothermal power plant	Alkaline electrolysis	Tanker + truck
40	Germany	PtL	Biogas plant	Wind onshore	Polymer electrolyte membrane EL	Truck
41	Germany	PtL	Lignite-fired power station	Wind onshore	Alkaline electrolysis	Truck
42	Germany	PtL	Lignite-fired power station	Electricity mix	Alkaline electrolysis	Truck

5.3.3.2.2.1 Global warming potential today

Figure 42 shows the results for the global warming potential (GWP) of the fully electricity-based methanol paths (PtL synthesis) for the year 2015. The process steps broken down in the results are described in more detail in Table 15. Path 42, in which the electricity for electrolysis comes from the German electricity mix, clearly comes off worst, which is due to the high proportion of fossil fuels in electricity generation. If the CO_2 from cement and lignite-fired power plants were to be allocated to methanol instead of just reporting it here for information, these paths would also perform just as badly or even worse than the conventional reference.

Figure 42: **Global warming potential 2015 of fully electricity-based methanol paths (full load hours synthesis plant)**



Source: own figure, ifeu

In all paths, electricity for electrolysis represents the largest share of the global warming potential. Paths 32 to 36 also reflect the high expenditure on equipment for CO_2 capture from the air. The paths with CO_2 capture from biogas plants (25, 40) are the most favourable. Several paths are in the range of 20 to 25 g CO_2eq/MJ product, which means a reduction of about 75% compared to conventional methanol.

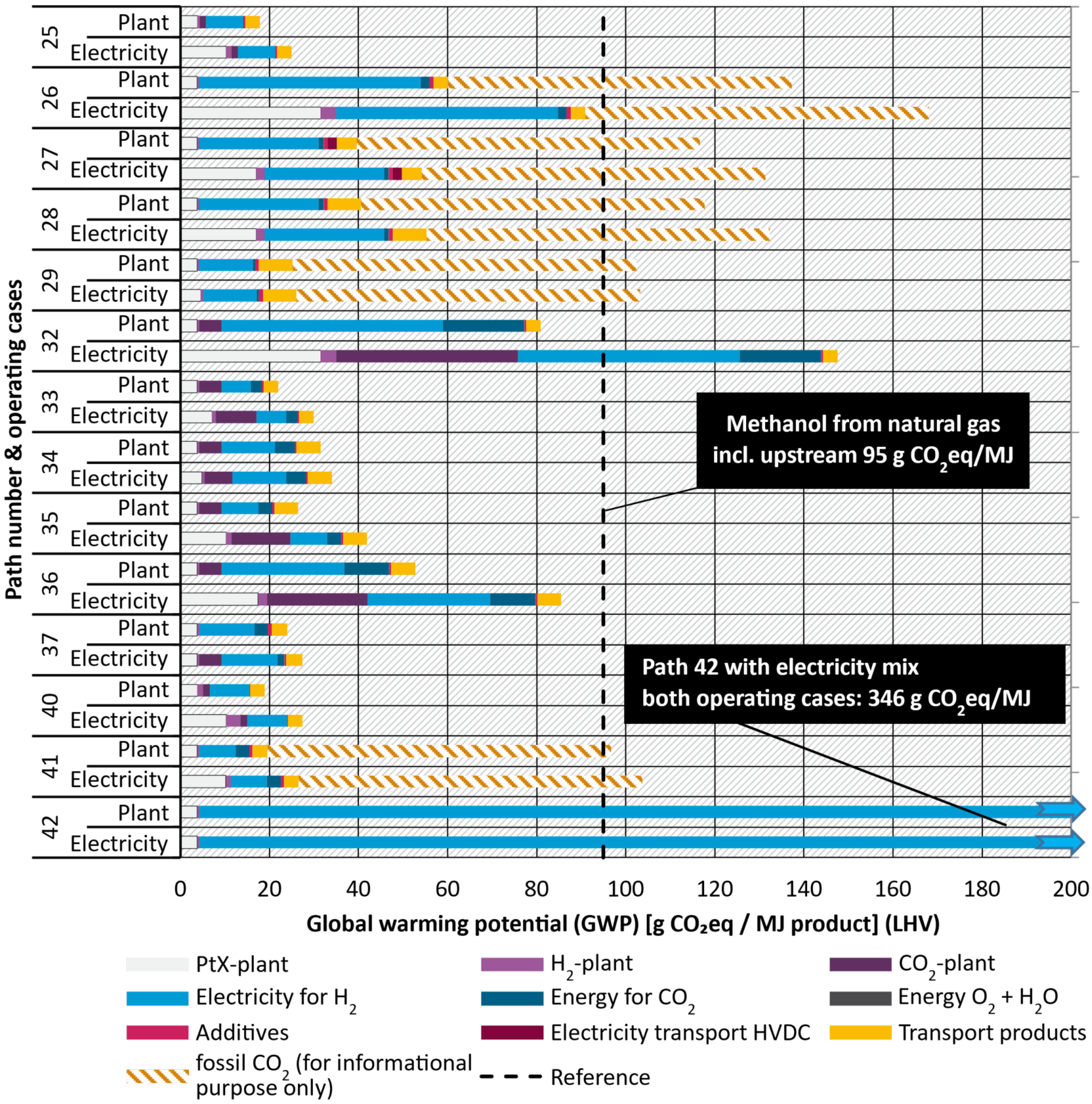
The influence of the power source also shows a similar picture to that of Fischer-Tropsch fuels. Paths with electricity from photovoltaic systems (e.g., 32 and 36) show a significantly higher global warming potential than otherwise identical paths where the electricity comes from wind turbines (33, 35) or concentrating solar power (34).

Since CO_2 capture from the air is energy-intensive and cannot be completely supplied from the waste heat of methanol synthesis in the reference year 2015, its contribution is also scaled with the power source used and its full-load hours. The transport of the liquid energy carriers, on the other hand, plays a subordinate role.

5.3.3.2.2.2 Second main case: global warming potential today depending on the mode of operation

As a second main case, the global warming potential of the electricity-based methanol paths in 2015 is calculated using the full-load hours of the electricity source. This approximates the case where the synthesis plant only runs when electricity is available from the linked electricity source (see Chapter 5.1.3.2). Figure 43 compares the results of both LCA calculations for global warming potential.

Figure 43: Global warming potential 2015 of fully electricity-based methanol paths (full-load hours of synthesis plant and full-load hours of power source)



Source: own figure, ifeu

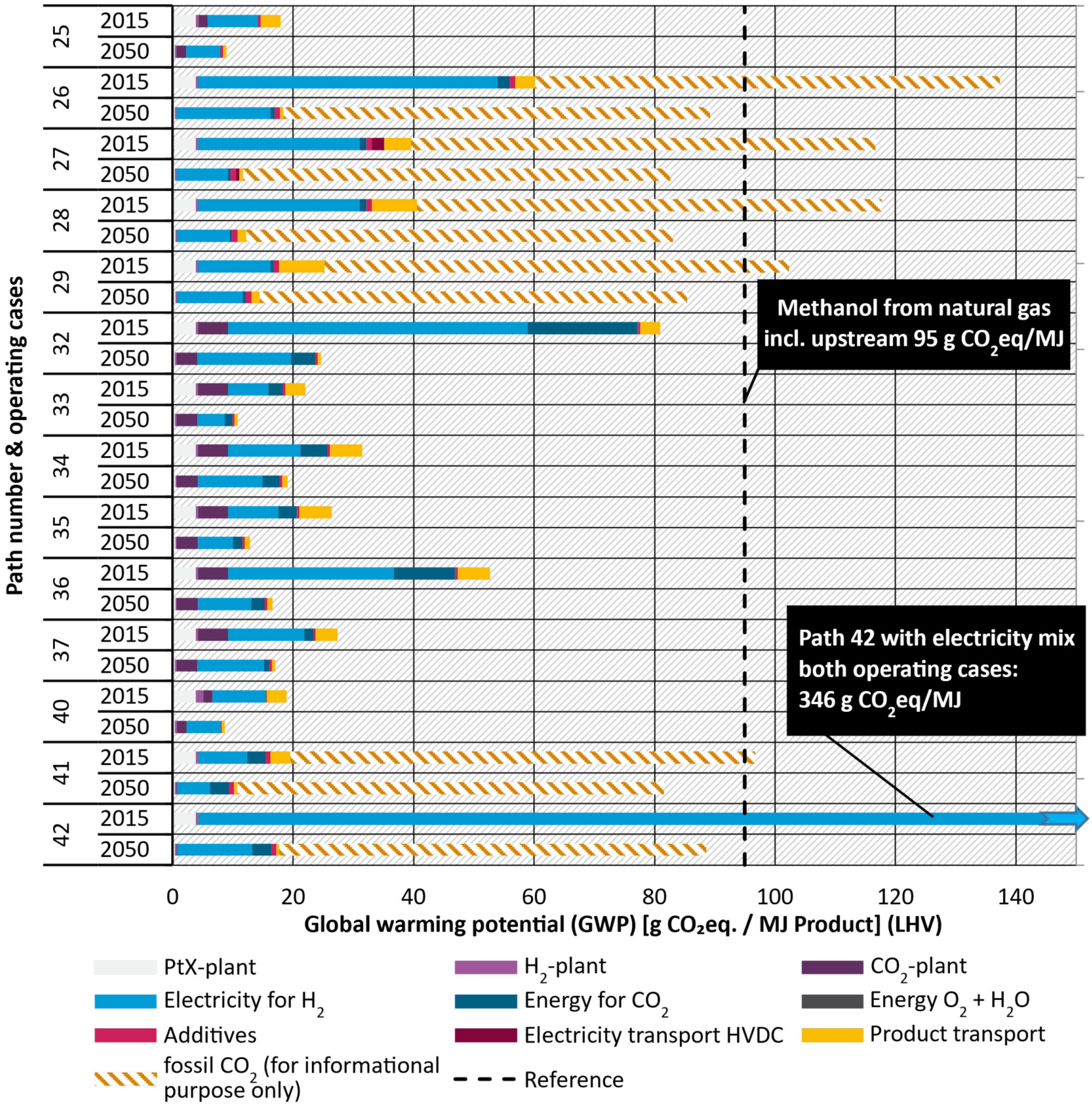
As in the case of Fischer-Tropsch fuels, the global warming potential of methanol production is greater over all paths in comparison with the calculation based on the full-load hours of the synthesis plant (Figure 42) – particularly clear for electricity sources with low full-load hours. The reason for this is again the higher contribution of the plant infrastructure. The environmental impacts arising from the construction of these plants are distributed over a lower product output at lower full-load hours and the same service life.

The increase is particularly marked for path 32 with photovoltaic systems in Germany as a source of electricity and CO_2 capture from the air. In the operating case "full load hours power source", the production of methanol leads to a GWP of 81 g CO_2eq/MJ product, in the operating case "full load hours synthesis plant" this is 148 g CO_2eq/MJ product. This corresponds to an increase of 83%.

5.3.3.2.2.3 Global warming potential 2050

Figure 44 compares the results for the global warming potential (GWP) of the fully electricity-based methanol paths (PtL synthesis) for the year 2050 with those for 2015. Compared with the results for 2015, the values have fallen by 35 to 95%. The sharpest decline is in path 42, where the electricity for electrolysis comes from the German electricity mix. In the course of the transformation to a climate-neutral economy (see chapter 5.1.2), its global warming potential decreases from 577 g CO_2eq. /kWh in 2010 to 14 g CO_2eq. /kWh in 2050 (Figure 34).

Figure 44: Global warming potential in 2050 and 2015 of fully electricity-based methanol paths (full-load hours synthesis plant)



Source: own figure, ifeu

The decrease for the other paths is also due to the decreasing global warming potential of electricity sources – especially wind power and photovoltaics. This is due to improved processes, higher secondary material quotas and the use of renewable energies in the production of steel, cement and silicon (Chapter 5.1.2) for the electricity generation plants. The GWP for paths with photovoltaics (26, 28, 32, 36) as the source is falling by around 70%, and by 45 to 55% for paths with wind power (25, 33, 35, 40, 41). The paths with concentrated solar power and geothermal energy (29, 34) improve by about 40%. The improved production of the synthesis plants also contributes, albeit small, to this positive development. Moreover, in 2050 methanol will be transported by tankers and trucks, which in turn will be powered by this fuel.

Most paths are in the range of 10 to 15 g CO_2eq/MJ product in 2050, which means a reduction of about 85 to 90% compared to conventional fuel.

5.3.3.2.2.4 Selected results in other impact categories

Table 22the ranges of results for all ten environmental impacts examined in this study for the fully electricity-based methanol paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the Federal Environment Agency's website. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts can be found in Chapter 5.3.4on cross-product analysis.

Table 22: Ranges of LCA results in 2050 of fully electricity-based methanol paths (full-load hours synthesis plant)

Environmental Impact	Reference	Min (path)	Max (path)	Comment
Global warming potential [g CO_2eq/MJ]	95	8.7 (40)	25 (32)	Most paths are between 10 and 20 g CO_2eq/MJ
Acidification [g SO_2eq/MJ]	0.052	0.082 (40)	4.9 (37)	Most paths are below 0.2 g SO_2eq/MJ
Eutrophication [g PO_4eq/MJ].	0.0065	0.015 (37)	0.097 (42)	Many paths are around 0.05 g PO_4eq/MJ.
Cumulative energy demand [MJ/MJ]	1.6	1.8 (41)	5.4 (37)	Many paths are between 1.9 and 2.5 MJ/MJ
Summer smog [g C_2H_4eq/MJ]	0.037	0.018 (37)	0.073 (32)	Many paths are between 0.025 and 0.050 g C_2H_4eq/MJ
Ozone depletion [g CFC11eq/MJ]	1.8E-05	1.1E-05 (25)	3.6E-04 (34)	Many paths are around 9.0E-05 g CFC11 eq/MJ
Particulate matter [g/MJ]	0.047	0.057 (40)	0.20 (32)	Many paths are around 0.13 g/MJ or less
Cumulative raw material demand [kg/MJ]	0.042	0.019 (37)	0.075 (32)	Many paths lie between 0.040 and 0.060 g/MJ
Land use [m^2a/MJ]	1.9E-04	7.4E-04 (41)	0.026 (32)	Paths with PV and CSP are significantly higher than those with wind, geothermal and electricity mix
Water demand [l/MJ]	0.048	0.13 (28)	3.8 (37)	Path 37 (geothermal energy) singularly high, most paths are between 0.13 and 0.46 l/MJ

As described in Chapter 5.3.3.2.2.3the values for **global warming potential** are between 8.7 and 25 g CO_2 eq/MJ. This corresponds to 9 and 26% of the fossil reference (the average global warming potential of methanol from natural gas, including the upstream chain). Paths 40 and 32 are the ones with the lowest and highest emissions. Most paths are between 10 and 20 g CO_2 eq/MJ. The main source is electricity generation for electrolysis.

For **acidification,** the values are between 0.082 and 4.9 g SO_2eq/MJ. This is between 160 and 7,600% of the fossil reference. Paths 40 and 37 are the ones with the lowest and highest emissions. Most paths are below 0.2 g SO_2eq/MJ. The main source is electricity generation for electrolysis – in an extreme way the direct emissions from the geothermal power plant in path 37.

The values for **eutrophication** are between 0.015 and 0.097 g PO_4eq/MJ. This is between 190 and 1,200% of the fossil reference. Paths 37 and 42 are the ones with the lowest and highest emissions. Many paths are around 0.05 g PO_4eq/MJ. The main source is electricity generation for electrolysis and in some paths the energy for CO_2 capture.

The **cumulative energy demand** is between 1.8 and 5.4 MJ/MJ. This corresponds to 110 and 340% of the fossil reference. Paths 41 and 37 are the ones with the lowest and highest emissions. Many paths are between 1.9 and 2.5 MJ/MJ. The main cause is electricity generation for electrolysis and CO_2 capture.

For the impact category **summer smog,** the values lie between 0.018 and 0.073g C_2H_4eq/MJ. This corresponds to 50 and 200% of the fossil reference. Paths 37 and 32 are the ones with the lowest and highest emissions. Many paths are between 0.025 and 0.050 g C_2H_4eq/MJ. The main source is electricity generation for electrolysis, but also the construction of the plants, in some paths the energy for CO_2 capture and the transport of the methanol from abroad (methanol-driven tankers) play a role.

The values for **ozone depletion range** from 1.1E-05 to 3.6E-04 g CFC11eq/MJ. This is between 55 and 180% of the fossil reference. Paths 25 and 34 are the ones with the lowest and highest emissions. Many paths are around 9.0E-05 g CFC11 eq/MJ. The main source is electricity generation in CSP power plants and the construction of facilities for the capture of CO_2 from the air.

For the impact category **particulate matter,** the values are between 0.057 and 0.20 g/MJ. This corresponds to 120 and 420% of the fossil reference. Paths 40 and 32 are the ones with the lowest and highest emissions. Many paths are around 0.13 g/MJ or below. The main sources are electricity generation for electrolysis, the construction of the plants and also the transport of methanol from abroad (methanol-driven tankers).

Cumulative raw material demand ranges from 0.019 to 0.075 g/MJ. This corresponds to 45 and 180% of the fossil reference. Paths 37 and 32 are the ones with the least and most effort. Many paths lie between 0.040 and 0.060 g/MJ. The main cause is electricity generation for electrolysis.

The values for **land use** are between 7.4E-04 and 2.6E-02 m^2a/MJ. This corresponds to 390 and more than 14,000% of the fossil reference. Paths 33 and 37 are the ones with the least and most impact. The main source is electricity generation for electrolysis, especially from photovoltaic systems.

The **water demand** is between 0.13 and 3.8 l/MJ. This corresponds to 275 and 7,900% of the fossil reference. Paths 28 and 37 are the ones with the lowest and highest demand respectively. Many paths are between 0.15 and 0.3 l/MJ. This is mainly due to the generation of electricity for electrolysis – in extreme cases in the geothermal power plant in path 15 – and the process water for methanol synthesis.

5.3.3.2.3 Results for biomass-based paths

To make the following result diagrams more readable, the biomass-based methanol supply paths are listed once again in Table 23. Only the path numbers are then noted on the diagrams.

Table 23: Biomass-based methanol supply paths

Path	Location	Synthesis	Biomass	Power source	Electrolysis	Transport
23	Germany	BtL	Straw	---	---	Truck
24	Germany	PBtL	Straw	Wind onshore	Alkaline electrolysis	Truck
30	Germany	BtL	Poplar wood from Short rotation coppices	---	---	Truck
31	Germany	PBtL	Poplar wood from Short rotation coppices	PVground	Alkaline electrolysis	Truck
38	Sweden	PBtL	Forest residue wood	Hydropower	Alkaline electrolysis	Tanker + truck
39	Sweden	PBtL	Poplar wood from Short rotation coppices	Hydropower	Alkaline electrolysis	Tanker + truck

5.3.3.2.3.1 Global warming potential today

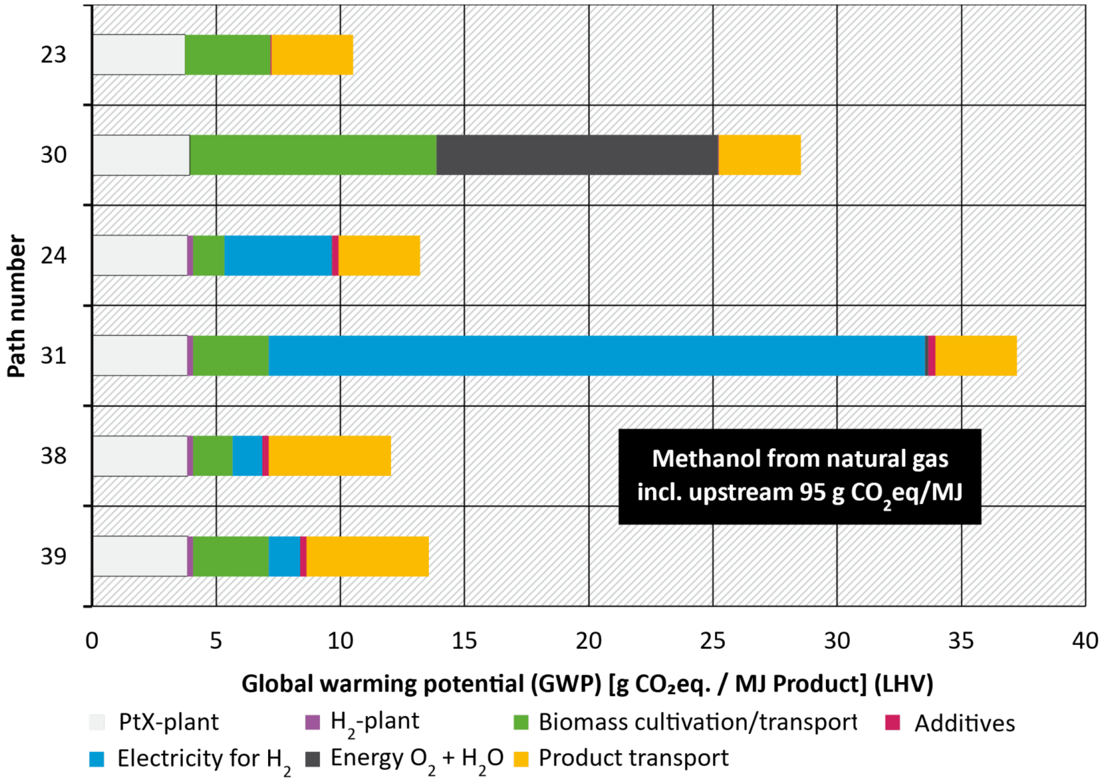
Figure 45 shows the results for the global warming potential (GWP) of the biomass-based methanol paths ((P)BtL synthesis) for the year 2015. The process steps broken down in the results are described in more detail in Table 15. In the case of the paths that do not use hydrogen (23, 30), biomass cultivation and transport account for a large share of the GWP. The larger value for path 30 reflects the higher emissions from the cultivation and harvesting of poplar wood from short-rotation plantations. The fact that less energy can be extracted from the methanol plant than from the Fischer-Tropsch plant means that more external energy has to be obtained to provide the oxygen for the gasification of the biomass by air separation. This is also reflected in path 30.

Paths 24 and 31 use the same substrates as paths 23 and 31 (straw and poplar wood), but make better use of them by adding hydrogen. Therefore, the contribution of biomass in these paths is lower. On the other hand, however, this adds the global warming potential of the electricity for electrolysis, which here comes from photovoltaic systems.

Path 38 and 39 combine the efficient use of poplar wood biomass with low GWP electricity sources. This results in an overall low GWP.

Many paths are in the range of 10 to 15 g CO_2eq/MJ product, which means a reduction of about 85 to 90% compared to conventional fuel. Path 31 achieves with 37 g CO_2eq/MJ product only a 50% reduction compared to the fossil reference.

Figure 45: Global warming potential 2015 of biomass-based methanol paths (full load hours synthesis plant)



Source: own figure, ifeu

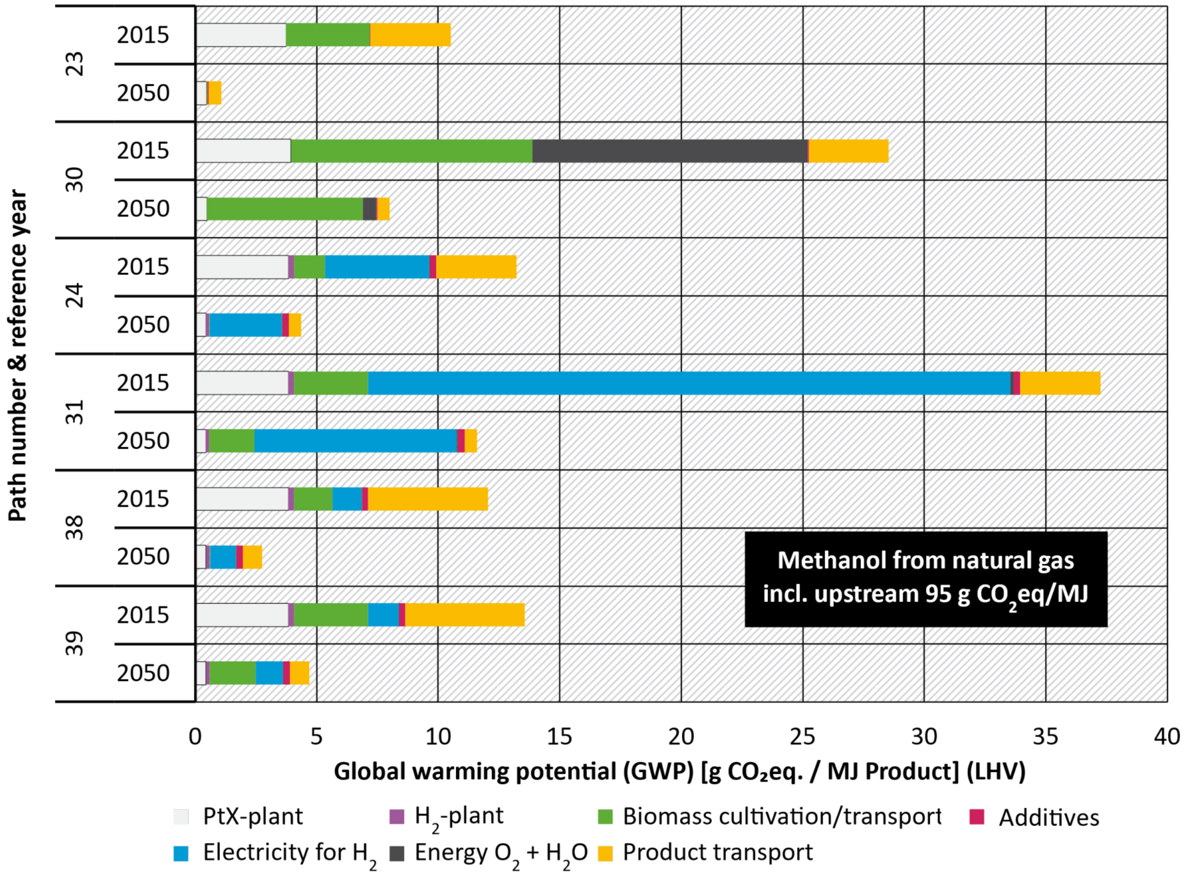
In the case of the biomass-based methanol paths, it does not make sense to present a second main case with the full load hours of the power source. The majority of the energy, carbon and hydrogen for the synthesis is obtained by these plants from the biomass used, the electricity only provides additional hydrogen for better utilisation of the carbon. This is either produced and stored in stock, or the plant is operated with the electricity mix in times of lack of electricity supply from renewable energy carriers.

5.3.3.2.3.2 Global warming potential 2050

Figure 46 compares the results for the global warming potential (GWP) of the biomass-based methanol paths ((P)BtL synthesis) for the year 2050 with those for 2015. Compared with the results for 2015, the values have fallen by 65 to 90%. The relatively sharpest decrease of 90% is in path 23, because the straw used there will be processed and transported by machines powered by PtX fuels in 2050. Transport and processing processes are also improving for the other paths. For the cultivated biomass poplar wood, this will reduce the GWP of biomass supply by about 40%.

Most paths are in the range of 4 g CO_2eq/MJ product in 2050, which means a reduction of about 96% compared to conventional fuel. Path 31 achieves an 87% reduction compared to the fossil reference with 12 g CO_2eq/MJ product.

Figure 46: **Global warming potential of biomass-based methanol paths in 2050 and 2015 (full load hours synthesis plant)**

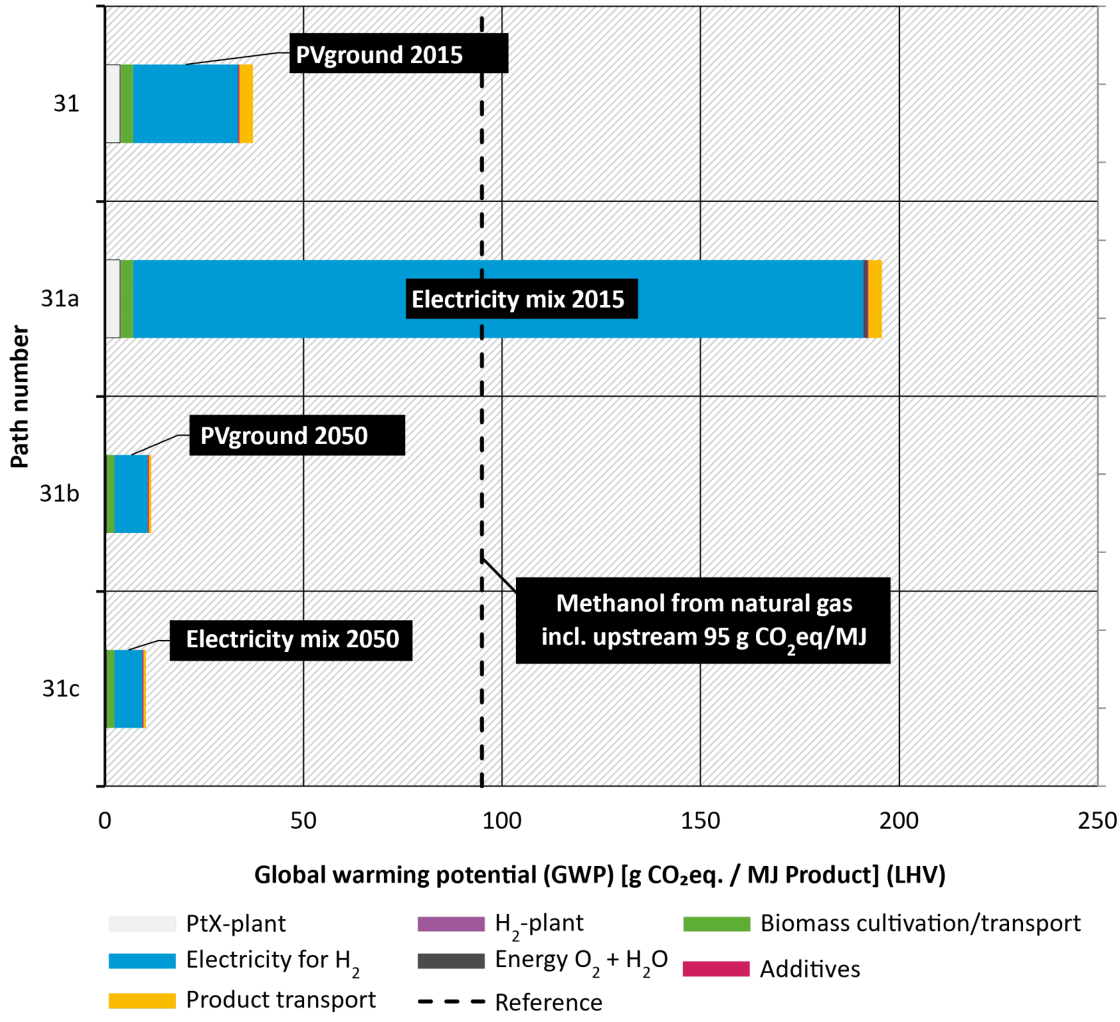


Source: own figure, ifeu

5.3.3.2.3.3 Sensitivity: global warming potential when operated with electricity mix

The global warming potential of the biomass-based methanol path 31 (MeOH-PBtL, SRC, PV ground, AEL) is calculated as the sensitivity, with electricity being drawn from the electricity mix. This represents the case where the synthesis plant continues to operate when electricity from the linked power source is not available. Figure 47 shows the results of these LCA calculations.

Figure 47: **Sensitivity path 31 (MS-PBtL SRC) with PV electricity and electricity mix 2015/2050 (full load hours synthesis plant)**



Source: own figure, ifeu

For the year 2015, the use of the electricity mix (path 31a) causes an increase in the global warming potential of path 31 from 37 to 196 g CO_2eq/MJ product. This is more than twice the reference value for fossil fuel. For the year 2050, however, the use of the electricity mix (path 31c, 10 g CO_2eq/MJ product) is even an advantage over the pure use of photovoltaics (path 31b, 12 g CO_2eq/MJ product), as done in path 31.

5.3.3.2.3.4 Selected results in other impact categories

Table 24 shows the ranges of the results for all ten environmental impacts examined in this study for the biomass-based methanol paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the Federal Environment Agency's website. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts can be found in Chapter 5.3.4on cross-product analysis.

Table 24: **Ranges of LCA results in 2050 mainly biomass-based methanol paths (full-load hours synthesis plant)**

Environmental Impact	Reference	Min (path)	Max (path)	Comment
Global warming potential g CO_2 eq/MJ	95	1.1 (23)	12 (31)	Most paths are between 3 and 8 g CO_2 eq/MJ
Acidification [g SO_2eq/MJ]	0.052	0.042 (38)	0.71 (30)	The paths with residual biomass (23, 24, 28) are below or just above the fossil reference
Eutrophication g PO_4eq/MJ].	0.0065	0.0045 (23)	0.14 (30)	Only one path (23) lies below the fossil reference
Cumulative energy demand [MJ/MJ]	1.6	1.9 (24)	3.5 (30)	The PBtL paths are cheaper than the BtL paths and lie between 1.9 and 2.2 MJ/MJ
Summer smog g C_2H_4eq/MJ	0.037	0.0092 (23)	0.034 (31)	Many paths lie around 0.015 g C_2H_4eq/MJ
Ozone depletion [g CFC11eq/MJ]	1.8E-05	6.7E-06 (38)	3.8E-04 (30)	Only the paths with residual biomass (23, 24, 28) are below the fossil reference
Particulate matter [g/MJ]	0.047	0.026 (23)	0.29 (30)	Only the paths with residual biomass (23, 24, 28) are below the fossil reference
Cumulative raw material demand [kg/MJ]	0.042	0.0074 (23)	0.034 (31)	Many paths are below 0.020 kg/MJ
Land use [m^2a/MJ]	1.9E-04	2.2E-04 (23)	4.2E-02 (30)	Large differences between residual and cultivated biomass
Water demand [l/MJ]	0.048	0.13 (23)	18 (30)	Large differences between residual and cultivated biomass

As described in Chapter 5.3.3.2.3.2 the values for **global warming potential** are between 1 and 12 g CO_2 eq/MJ. This corresponds to 1.1 and 12% of the fossil reference value (the average global warming potential of methanol from natural gas, including the upstream chain). Paths 23 and 31 are the ones with the lowest and highest emissions. Most paths are between 3 and 8 g CO_2 eq/MJ. The main sources are electricity generation for electrolysis and the cultivation of wood from short rotation coppices.

For **acidification,** the values are between 0.042 and 0.71 g SO_2eq/MJ. This is between 80 and 1,100% of the fossil reference. Paths 38 and 30 are the ones with the lowest and highest emissions. Three paths are below or just above the fossil reference of 0.052 g SO_2eq/MJ. The main source is the cultivation of wood from short rotation coppices.

The values for **eutrophication** are between 0.0045 and 0.14 g PO_4eq/MJ. This corresponds to 70 and 2,200% of the fossil reference. Paths 23 and 30 are the ones with the lowest and highest emissions. Only one path (23) is below the fossil reference of 0.007 g PO_4eq/MJ. The main sources are electricity generation for electrolysis and the cultivation of wood from short rotation coppices.

The **cumulative energy demand** is between 1.9 and 3.5 MJ/MJ. This corresponds to 120 and 220% of the fossil reference. Trails 24 and 30 are the least and most energy intensive. The PBtL paths are cheaper than the BtL paths and range between 1.9 and 2.2 MJ/MJ. The main causes are the generation of electricity for electrolysis and the cultivation and transport of the biomass.

For the impact category **summer smog,** the values lie between 0.0092 and 0.034 g C_2H_4eq/MJ. This corresponds to 24 and 92% of the fossil reference. Paths 23 and 31 are the ones with the lowest and highest emissions. Many paths are around 0.015 g C_2H_4eq/MJ. The main sources are electricity generation for electrolysis and cultivation and transport of the biomass.

For **ozone depletion,** the values are between 6.7E-06 and 3.8E-04 g CFC11eq/MJ. This is between 40 and 2,100% of the fossil reference. Paths 38 and 30 are the ones with the lowest and highest emissions. Only the paths with residual biomass (23, 24, 28) are below the fossil reference of 1.8E-05 g CFC11 eq/MJ. The main source is the cultivation of wood from short rotation coppices.

For the impact category **particulate matter,** the values are between 0.026 and 0.29 g/MJ. This corresponds to 60 and 620% of the fossil reference. Paths 23 and 30 are the ones with the lowest and highest emissions. Only the paths with residual biomass (23, 24, 28) are below the fossil reference of 0.047 g/MJ. The main sources are electricity generation for electrolysis and biomass cultivation.

Cumulative raw material demand ranges from 0.0074 to 0.034 kg/MJ. This corresponds to 17 and 91% of the fossil reference. Paths 23 and 31 are the ones with least and most demand. Many paths are below 0.020 kg/MJ. The main cause is electricity generation for electrolysis.

The values for **land use** are between 2.2E-04 and 4.2E-02 m^2a/MJ. This corresponds to 115 and more than 22,000% of the fossil reference. Paths 23 and 30 are the ones with the least and most impacts. The main sources are the cultivation of wood from short rotation coppices and the generation of electricity for electrolysis, in particular from photovoltaic systems.

The **water demand** is between 0.13 and 18 l/MJ. This corresponds to 260 and 38,000% of the fossil reference. The paths 23 and 30 are again the ones with the lowest and highest demand. The PBtL paths with wood from short-rotation plantations are around 5.8 l/MJ, and the PBtL paths with residues are around 0.3 l/MJ. The main reason for this is the cultivation of wood from short rotation coppices.

5.3.3.3 Synthetic natural gas

5.3.3.3.1 Brief overview, comments on data quality and technological maturity

Methane synthesis based on CO_2 is a technology with a high degree of maturity. During the reaction, a lot of heat is released which can be used in CO_2 capture or high-temperature electrolysis. This heat integration is assumed throughout the paths studied here.

Production data for methane synthesis were taken from the literature on the Audi AG demonstration plant in Werlte. The high level of heat integration implemented in this plant was assumed. The data thus possibly reflect a rather optimistic view.

5.3.3.3.2 Results

To make the following result diagrams more readable, the fully electricity-based supply paths for synthetic methane are listed again in Table 25. Only the path numbers are then noted on the diagrams.

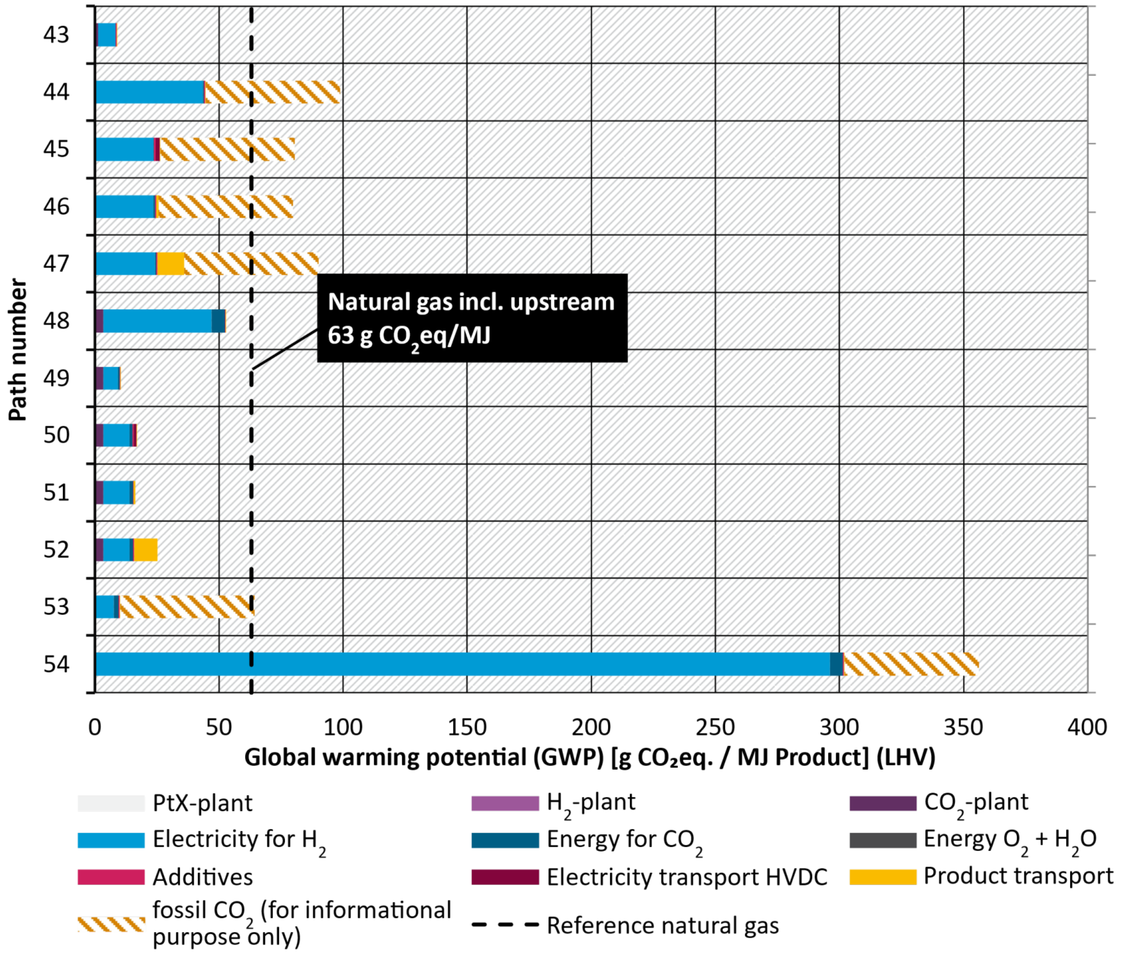
Table 25: Supply paths for synthetic natural gas

Path	Location	Synthesis	CO_2 source	Power source	Electrolysis	Transport
43	Germany	PtG	Biogas plant	Wind onshore	Alkaline electrolysis	Gas grid
44	Germany	PtG	Cement plant	PV ground	Alkaline electrolysis	Gas grid
45	Germany	PtG	Cement plant	PV ground	Alkaline electrolysis	HVDC + gas grid
46	Saudi Arabia	PtG	Cement plant	PV ground	Alkaline electrolysis	Pipeline
47	Saudi Arabia	PtG	Cement plant	PV ground	Alkaline electrolysis	Tanker + gas grid
48	Saudi Arabia	PtG	DAC (air)	PV ground	Alkaline electrolysis	Gas grid
49	Germany	PtG	DAC (air)	Wind offshore	Alkaline electrolysis	Gas grid
50	Morocco	PtG	DAC (air)	Solar power plant (CSP)	Alkaline electrolysis	HVDC + gas grid
51	Morocco	PtG	DAC (air)	Solar power plant (CSP)	Alkaline electrolysis	Pipeline
52	Morocco	PtG	DAC (air)	Solar power plant (CSP)	Alkaline electrolysis	Tanker + gas grid
53	Germany	PtG	Lignite-fired power station	Wind onshore	Alkaline electrolysis	Gas grid
54	Germany	PtG	Lignite-fired power station	Electricity mix	Alkaline electrolysis	Gas grid

5.3.3.3.2.1 Global warming potential today

Figure 48 shows the results for the global warming potential (GWP) of the paths for synthetic natural gas (PtG synthesis) for the year 2015. The process steps broken down in the results are described in more detail in Table 15. Path 54, in which the electricity for electrolysis comes from the German electricity mix, clearly comes off worst, which is due to the high share of fossil fuels in electricity generation. If the CO_2 from cement and lignite-fired power plants were to be allocated to synthetic natural gas instead of just reporting it here, these paths would also perform almost as badly or even worse than the conventional reference.

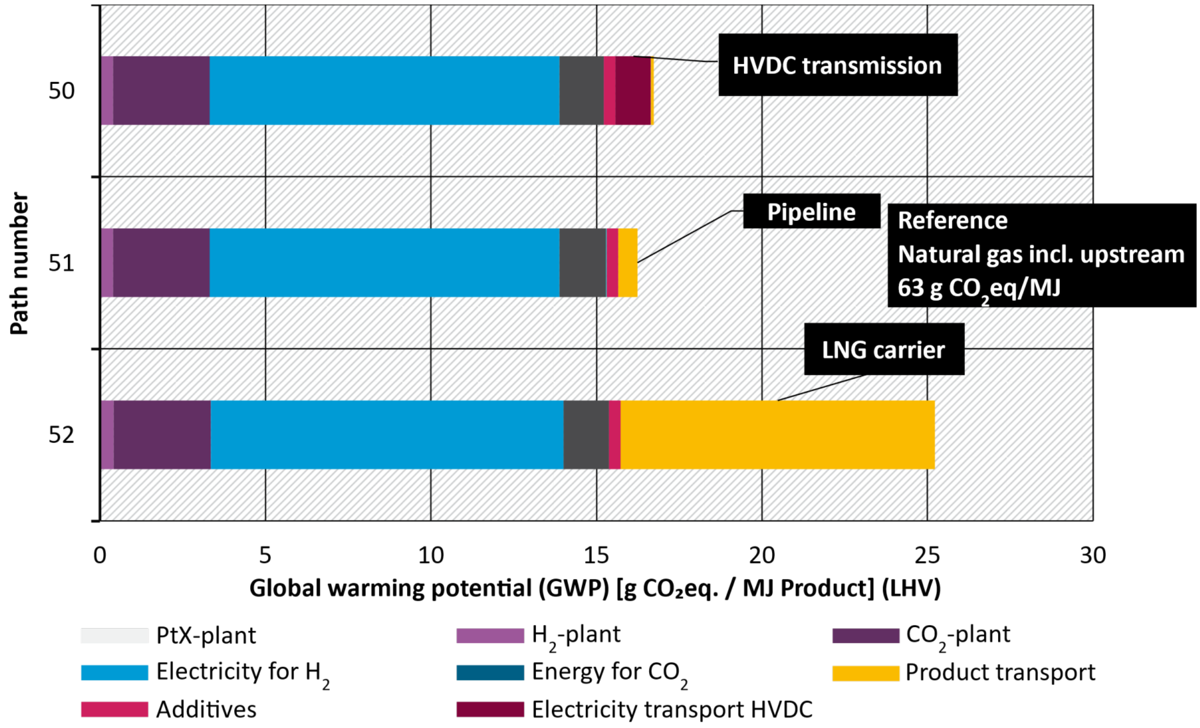
Figure 48: Global warming potential 2015 supply paths for synthetic natural gas (full-load hours of synthesis plant)



Source: own figure, ifeu

The fact that transport also plays a greater role in (synthetic) natural gas than in liquid energy carriers and can have a considerable impact on the global warming potential is shown in Figure 49. The paths 50 to 52 shown there all contain a CO_2 capture from the air. Concentrating solar power (CSP) is used as the power source. The power plant is located in Morocco – but while in paths 51 and 52 the product is transported to Germany by pipeline or ship, in path 50 the electricity reaches Germany via high-voltage direct current transmission, where the natural gas is then synthesised. The transport of electricity causes greenhouse gas emissions due to the construction of the pipeline and losses during transmission, which per unit of the product are about twice as high as those generated when the natural gas is transported to Germany by pipeline. However, at around 1 g CO_2eq/MJ product, the contribution to the overall result is small (6%). Transport by liquefied natural gas tanker is much less favourable. Since methane is released during the liquefaction and regasification of natural gas and the gas-powered engines of the tankers also have a considerable methane slip, the transport is responsible for around 10 g of CO_2eq/MJ product for this path. This represents almost 40% of the total emissions of this path.

Figure 49: Transport modes and global warming potential 2015 for synthetic natural gas supply paths (full-load hours of synthesis plant)

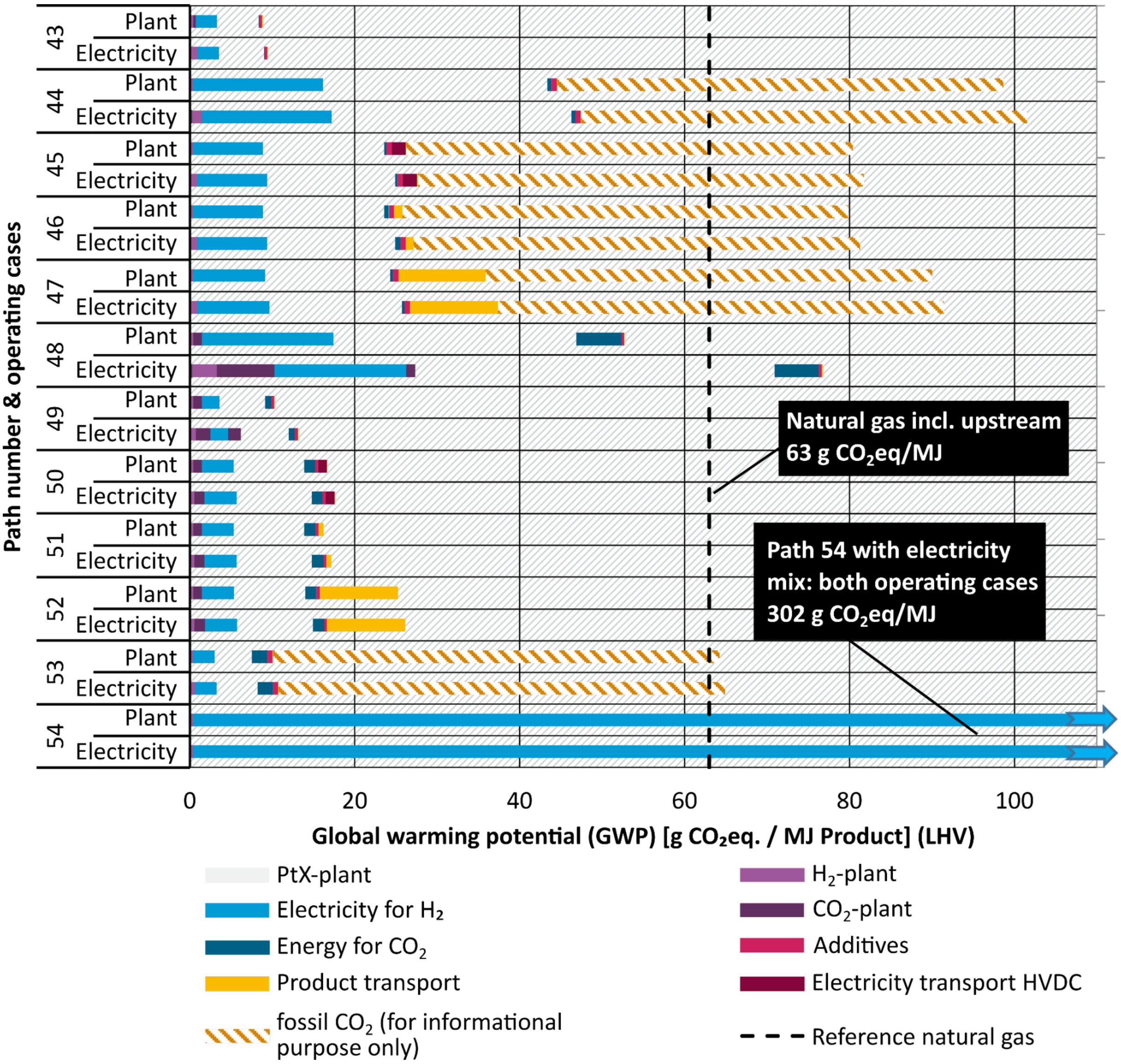


Source: own figure, ifeu

5.3.3.3.2.2 Second main case: global warming potential today depending on the mode of operation

As a second main case, the global warming potential of the SNG paths 2015 is again calculated using the full-load hours of the power source. This approximates the case where the synthesis plant only runs when electricity is available from the linked power source (see Chapter 5.1.3.2). Figure 50 shows the results of these LCA calculations.

Figure 50: **Global warming potential 2015 supply paths of synthetic natural gas (full-load hours of synthesis plant and full-load hours of power source)**



Source: own figure, ifeu

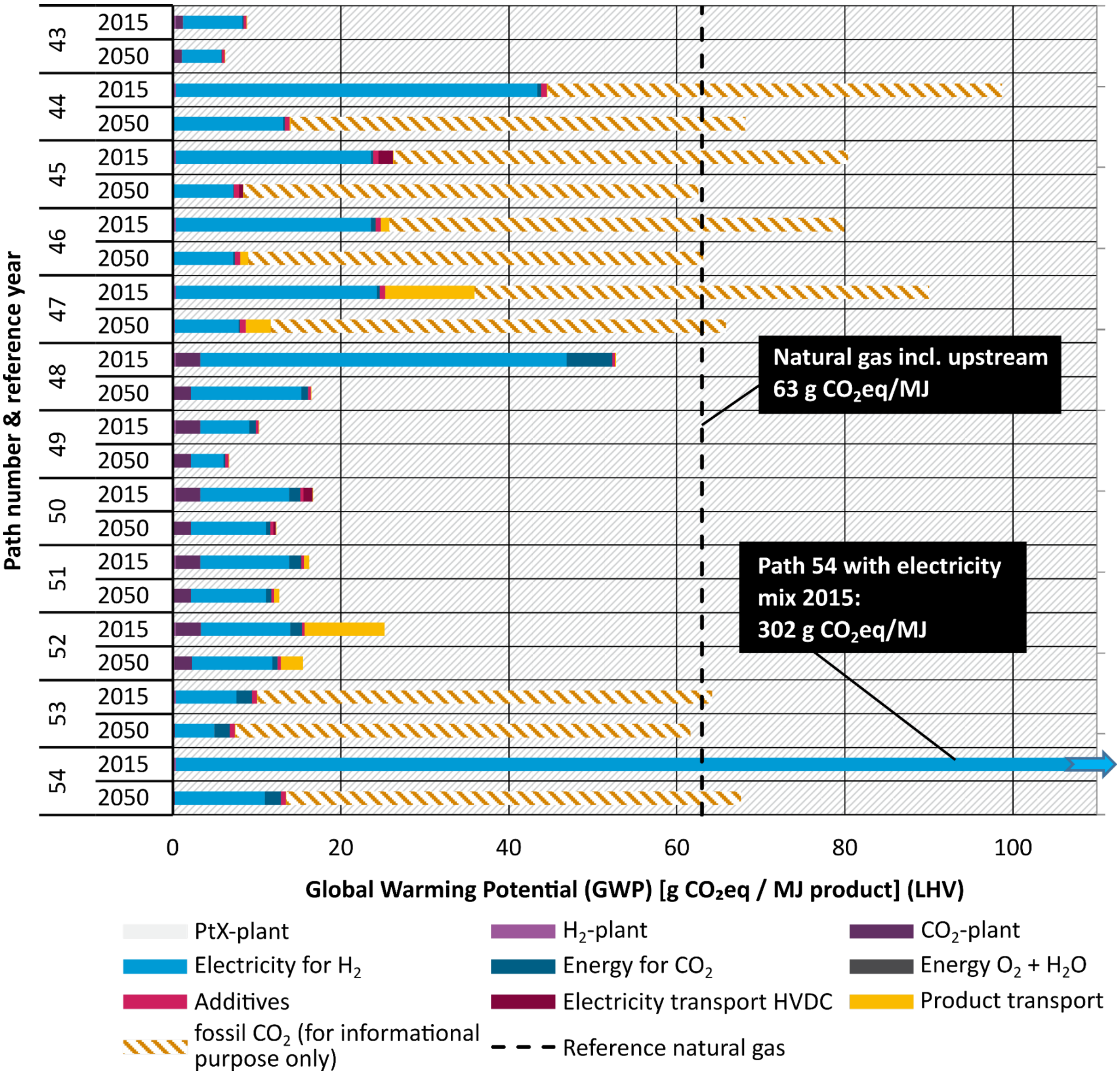
As with Fischer-Tropsch fuels and methanol, the global warming potential of natural gas production increases across all paths compared with the calculation using the full-load hours of the synthesis plant. The reason for this is the higher contribution of the plant infrastructure. The environmental impacts arising from the construction of these plants are distributed over a lower product output at lower full-load hours and the same service life. However, the contribution of the synthesis plant to the production of synthetic natural gas is not as large as for liquid energy carriers. This is due to the different EcoInvent modules used in the model ("chemical factory construction, organics" for methanol and Fischer-Tropsch syntheses and "synthetic gas factory construction" for SNG). A difference between the plants is to be expected because natural gas synthesis is simpler. However, the difference calculated here appears to be very large. However, specific plant data were not available for this study.

For path 48 with photovoltaic systems in Germany as a source of electricity and CO_2 capture from the air, the increase is more pronounced than for the other paths. In the "full-load hours power source" mode of operation, the production of SNG here results in a GWP of 77 g CO_2eq/MJ product; in the "full-load hours synthesis plant" mode of operation, this is 53 g CO_2eq/MJ product. This corresponds to an increase of 45%, which here is mainly due to the production of the CO_2 capture plant. Material data from the manufacturer were available for these.

5.3.3.3.2.3 Global warming potential 2050

Figure 51 compares the results for the global warming potential (GWP) of the paths for synthetic natural gas (PtG synthesis) for the year 2050 with those for 2015. Compared with the results for 2015, the values have fallen by 22 to 96%. The sharpest decrease is in path 54, where the electricity for electrolysis comes from the German electricity mix. During the transformation to a climate-neutral economy (see Chapter 5.1.2), its global warming potential falls from 577 g CO_2eq/kWh in 2010 to 14 g CO_2eq/kWh in 2050 (Figure 34).

Figure 51: Global warming potential in 2050 and 2015 supply paths of synthetic natural gas (full-load hours of synthesis plant)



Source: own figure, ifeu

The decline for the other paths is also due to the lower global warming potential of the electricity sources – especially wind power and photovoltaics. The reasons are: improved processes, higher secondary material quotas and the use of renewable energies in the production of steel, cement and silicon (Chapter 5.1.2). The GWP for paths with photovoltaic (44, 45, 46, 47, 48) as the source decreases by around 70%, and by 30 to 40% for paths with wind-generated electricity (43, 49, 53, 55, 56). The paths with concentrated solar power (50 to 52) improve by around 13%. The improved production of the synthesis plants also contributes, albeit small, to this positive development.

Most paths are in the range of 7 to 15 g CO_2eq/MJ product in 2050, which means a reduction of about 80 to 90% compared to fossil natural gas.

5.3.3.3.2.4 Selected results in other impact categories

Table 26 shows the ranges of results for all ten environmental impacts studied in this study for the paths of synthetic natural gas for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the Federal Environment Agency's website. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts can be found in Chapter 5.3.4 on cross-product analysis.

Table 26: Ranges of LCA results 2050 paths synthetic natural gas (full-load hours synthesis plant)

Environmental Impact	Reference	Min (path)	Max (path)	Comment
Global warming potential [g CO_2 eq/MJ]	63	6.3 (43)	17 (48)	Most paths are between 8 and 13 g CO_2 eq/MJ
Acidification [g SO_2eq/MJ]	0.032	0.075 (49)	0.26 (54)	Most paths are around 0.10 g SO_2eq/MJ
Eutrophication [g PO_4eq/MJ].	0.0015	0.016 (49)	0.073 (54)	Many paths lie between 0.020 and 0.035 g PO_4eq/MJ
Cumulative energy demand [MJ/MJ]	1.01	1.5 (43)	1.8 (48)	
Summer smog [g C_2H_4eq/MJ]	0.020	0.018 (49)	0.049 (48)	Many paths are between 0.025 and 0.030 g C_2H_4eq/MJ.
Ozone depletion [g CFC11eq/MJ]	1.1E-05	7.7E-06 (43)	2.5E-04 (52)	Many paths are around 2.8E-05 g CFC11eq/MJ
Particulate matter [g/MJ]	0.022	0.060 (49)	0.15 (54)	Many paths are around 0.08 g/MJ
Cumulative raw material demand [kg/MJ]	0.026	0.019 (49)	0.048 (48)	
Land use [m^2a/MJ]	5.4E-08	4.6E-04 (53)	1.8E-02 (48)	Paths with PV and CSP significantly worse than those with wind and electricity mix
Water demand [l/MJ]	1.1E-04	9.4E-02 (46)	2.7E-01 (48)	

As described in Chapter 5.3.3.3.2.3 the values for **global warming potential** range between 6.3 and 17 g CO_2 eq/MJ. This corresponds to 10 and 27% of the fossil reference (the average global warming potential of natural gas including upstream chain). Paths 43 and 48 are the ones with the lowest and highest emissions. Most paths are between 8 and 13 g CO_2 eq/MJ. The main sources are electricity generation for electrolysis, construction of the facilities for CO_2 capture from the air and transport of the SNG by ship.

For **acidification** the values are between 0.075 and 0.26 g SO_2eq/MJ. This corresponds to 230 and 800% of the fossil reference. Paths 49 and 54 are the ones with the lowest and highest emissions. Most paths are around 0.100 g SO_2eq/MJ. The main sources are electricity generation for electrolysis and production and consumables for electrolysers.

For **eutrophication,** the values are between 0.016 and 0.073 g PO_4eq/MJ. This corresponds to 1,000 and 4,900% of the fossil reference. Paths 49 and 54 are the ones with the lowest and highest emissions. Many paths are between 0.020 and 0.035 g PO_4eq/MJ. The main source is electricity generation for electrolysis and lignite for capture energy from the lignite-fired power plant.

The **cumulative energy demand** is between 1.5 and 1.8 MJ/MJ. This corresponds to 150 and 180% of the fossil reference. Paths 43 and 48 are the ones with the lowest and highest emissions. The main cause is electricity generation for electrolysis.

For the impact category **summer smog,** the values lie between 0.018 and 0.049 g C_2H_4eq/MJ. This corresponds to 90 and 245% of the fossil reference. Paths 49 and 48 are the ones with the lowest and highest emissions. Many paths are between 0.025 and 0.030 g C_2H_4eq/MJ. The main source is electricity generation for electrolysis, but the construction of the DAC plants and transport by LNG tankers each contribute around 20% of the total.

For **ozone depletion,** the values are between 7.7E-06 and 2.5E-04 g CFC11eq/MJ. This is between 70 and 2,300% of the fossil reference. Paths 49 and 48 are the ones with the lowest and highest emissions. Many paths are around 2.8E-05 g CFC11eq/MJ. The main source is electricity generation for electrolysis, construction of the facilities for capturing CO_2 from the air and transport by LNG tanker.

For the impact category **particulate matter,** the values are between 0.06 and 0.15 g/MJ. This corresponds to 270 and 680% of the fossil reference. Paths 49 and 54 are the ones with the lowest and highest emissions. Many paths are around 0.08 g/MJ. The main sources are electricity generation for electrolysis, construction of the plants and transport by LNG tanker.

Cumulative raw material demand ranges from 0.019 to 0.048 kg/MJ. This corresponds to 73 and 185% of the fossil reference. Paths 49 and 48 are the ones with the lowest and highest emissions. The main cause is electricity generation for electrolysis.

The values for **land use** are between 4.6E-04 and 1.8E-02 m^2a/MJ. This corresponds to 850,000 and 33,000,000% of the fossil reference. Paths 53 and 48 are the ones with the least and most impacts. The main source is electricity generation for electrolysis, especially from photovoltaic systems.

The **water demand** is between 0.094 and 0.27 l/MJ. This corresponds to 85,000 and 250,000% of the fossil reference. Paths 46 and 48 are the ones with the lowest and highest emissions. Many paths are around 0.300 l/MJ. This is mainly due to electricity generation for electrolysis and process water uses at the sites without desalination.

5.3.3.4 Biomethane

5.3.3.4.1 Brief overview, comments on data quality and technological maturity

Biomethane production through fermentation of biomass and subsequent purification of the raw gas is a technology with the highest degree of maturity. The paths considered here differ on the one hand in the substrates used and on the other hand in the processes for CO_2 capture.

There are different technical possibilities to provide the energy for the operation of the biogas plant and the upgrading of the raw gas/CO_2 capture. In the plants modelled here, a biogas cogeneration plant is used. The environmental burdens are divided between electricity and heat according to exergy content.

5.3.3.4.2 Results

To make the following result diagrams easier to read, the paths for biomethane production are listed again in Table 27. Only the path numbers are then noted on the diagrams.

Table 27: Biomethane supply paths

Path	Location	Synthesis	Biomass	Separation technology	Transport
57	Germany	Fermentation	Organic waste/ green cuttings	Amine scrubbing	Gas grid
58	Germany	Fermentation	Maize/slurry	Amine scrubbing	Gas grid
59	Germany	Fermentation	Organic waste/ green cuttings	Pressure water scrubbing	Gas grid
60	Germany	Fermentation	Organic waste/ green cuttings	Membrane separation	Gas grid

5.3.3.4.2.1 Global warming potential today

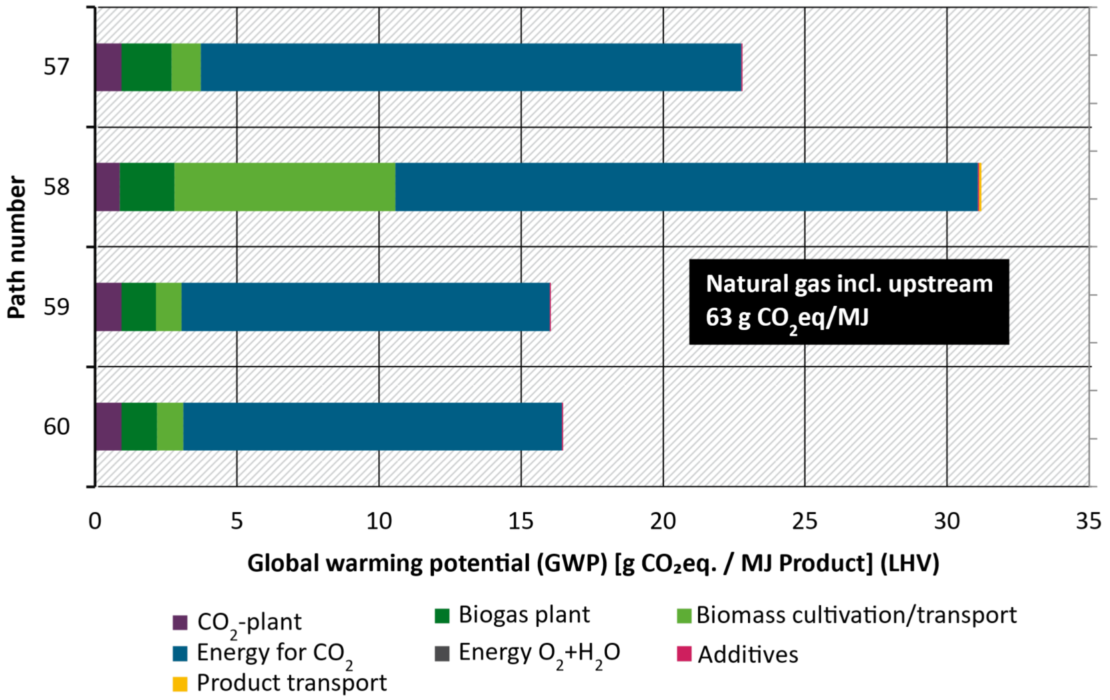
Figure 52 shows the results for the global warming potential (GWP) of the biomethane paths for the year 2015. The process steps broken down in the results are described in more detail in Table 15.

Path 58, which uses a mixture of maize as a crop biomass and liquid manure (slurry) as an agricultural residue, is performing the worst. The cultivation of maize requires energy for field preparation and harvesting, and fertilisation releases nitrogen compounds that contribute significantly to the GWP.

Heat and electricity for CO_2 capture are generated in the plants adopted here from a combined heat and power plant running on raw biogas. Escaping methane (methane slip) is responsible for the global warming potential of CO_2 capture. There are no major differences in global warming potential between the CO_2 capture processes of pressurised water scrubbing (path 59) and membrane separation (path 60). Amine scrubbing (paths 57, 58), on the other hand, performs slightly worse.

The two best paths are in the range of 15 g CO_2eq/MJ biomethane, which means a reduction of about 75% compared to fossil methane. For path 58 with cultivated biomass the reduction is only 45%.

Figure 52: **Global warming potential 2015 biomethane supply paths (full-load hours of synthesis plant)**

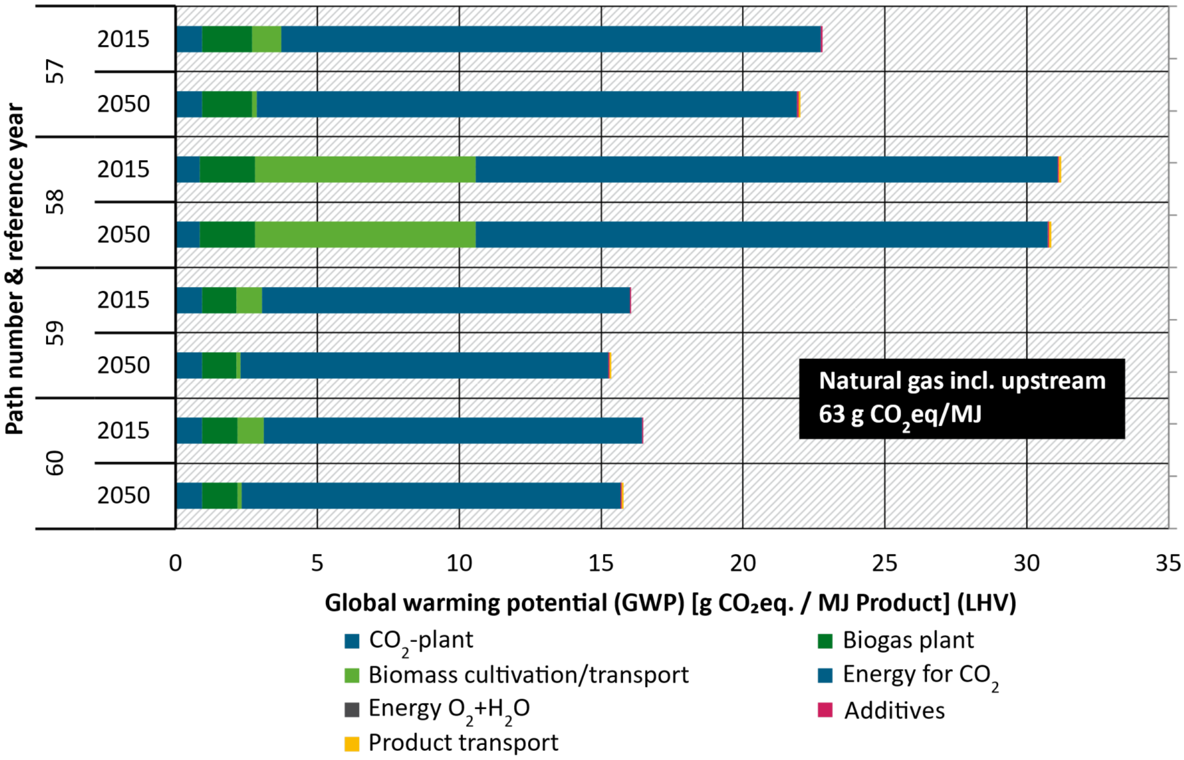


Source: own figure, ifeu

5.3.3.4.2.2 Global warming potential 2050

Figure 53 compares the results for the global warming potential (GWP) of the biomethane paths for the year 2050 with those for 2015. Compared with the results for 2015, the values have barely dropped. As main source remains the methane slip in the energy supply for CO_2 capture.

Figure 53: **Global warming potential in 2050 and 2015 biomethane supply paths (full-load hours of synthesis plant)**



Source: own figure, ifeu

5.3.3.4.2.3 Selected results in other impact categories

In Table 28 the ranges of the results for all ten environmental impacts examined in this study are shown for the biomethane paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and operating cases can be found on the Federal Environment Agency's website. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts can be found in Chapter 5.3.4 on cross-product analysis.

Table 28: Ranges of life cycle assessment results in 2050 biomethane paths (full load hours synthesis plant)

Environmental Impact	Reference	Min (path)	Max (path)	Comment
Global warming potential [g CO_2 eq/MJ	63	15 (59)	31 (58)	
Acidification [g SO_2eq/MJ]	0.032	0.043 (59)	0.31 (58)	The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60).
Eutrophication [g PO_4eq/MJ].	0.0015	0.016 (59)	0.064 (58)	The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60).
Cumulative energy demand [MJ/MJ]	1.01	0.048 (59)	0.82 (58)	Paths with residual biomass significantly better than those with cultivated biomass
Summer smog [g C_2H_4eq/MJ]	0.020	0.024 (59)	0.24 (58)	The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60).
Ozone depletion [g CFC11eq/MJ]	1.1E-05	3.5E-04 (59)	5.8E-04 (58)	
Particulate matter [g/MJ]	0.022	0.042 (59)	0.33 (58)	The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60).
Cumulative raw material demand [kg/MJ]	0.026	0.012 (59)	0.055 (58)	Paths with residual biomass significantly better than path 58 cultivated biomass
Land use [m^2a/MJ]	5.4E-08	9.0E-04 (59)	1.3E-02 (58)	Paths with residual biomass significantly better than path 58 cultivated biomass
Water demand [l/MJ]	1.1E-04	2.1E-02 (60)	5.6 (58)	Paths with residual biomass significantly better than path 58 cultivated biomass

As described in Chapter 5.3.3.4.2.2 the values for **global warming potential** are between 15 and 31 g CO_2 eq/MJ. This corresponds to 24 and 49% of the fossil reference (the average global warming potential of natural gas including upstream chain). Paths 59 and 58 are the ones with the lowest and highest emissions. The main sources are the energy supply for CO_2 capture and the cultivation and transport of the cultivated biomass.

For **acidification,** the values are between 0.043 and 0.31 g SO_2eq/MJ. This is between 130 and 1,000% of the fossil reference. Paths 59 and 58 are the ones with the lowest and highest emissions. The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60). The main sources are the energy supply for CO_2 capture including amine losses and the cultivation and transport of the cultivated biomass.

The values for **eutrophication** are between 0.016 and 0.064 g PO_4eq/MJ. This corresponds to 1,000 and 4,200% of the fossil reference. The paths 59 and 58 are the ones with the lowest and highest emissions. In this category too, the paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60). The main sources are the energy supply for CO_2 capture and the cultivation and transport of the cultivated biomass.

The **cumulative energy demand** is between 0.048 and 0.82 MJ/MJ. This corresponds to 5 and 82% of the fossil reference. Paths 59 and 58 are the ones with the lowest and highest energy expenditure. The main causes are cultivation and transport of the cultivated biomass.

For the impact category **summer smog,** the values lie between 0.024 and 0.24 g C_2H_4eq/MJ. This corresponds to 120 and 1,200% of the fossil reference. Paths 59 and 58 are the ones with the lowest and highest emissions. In this category too, the paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60). The main source is the energy supply for CO_2 capture.

The values for **ozone depletion** range from 3.5E-04 to 5.8E-04 g CFC11eq/MJ. This is between 3,100 and 5,300% of the fossil reference. Paths 59 and 58 are the ones with the lowest and highest emissions. The main sources are the energy supply for CO_2 capture and the cultivation and transport of the cultivated biomass.

For the impact category **particulate matter,** the values are between 0.042 and 0.33 g/MJ. This corresponds to 190 and 1,500% of the fossil reference. Paths 59 and 58 are the ones with the lowest and highest emissions. The paths with amine scrubbing (57 and 58) perform significantly worse than those with pressurised water scrubbing (59) and membrane separation (60). The main sources are the energy supply for CO_2 capture including amine losses and the cultivation and transport of the cultivated biomass.

The **cumulative raw material demand** is between 0.012 and 0.055 kg/MJ. This corresponds to 46 and 210% of the fossil reference. Paths 59 and 58 are the ones with the least and most demand. The main sources are construction of the plants and cultivation and transport of the cultivated biomass.

The values for **land use** are between 9.0E-04 and 1.3E-02 m^2a/MJ. This corresponds to 1,700,000 and 24,000,000% of the fossil reference. Paths 59 and 58 are the ones with the least and most impacts. The main causes are the construction of the biogas plants and the cultivation and transport of the cultivated biomass.

The **water use** is between 0.021 and 5.6 l/MJ. This corresponds to 19,000 and 5,000,000% of the fossil reference. Paths 60 and 58 are the ones with the lowest and highest demand respectively. The paths with residual biomass are all around 0.025 l/MJ. The main cause there is the construction and operation of the plants. In path 58, the high water demand is due to the cultivation of the cultivated biomass maize.

5.3.3.5 Hydrogen

5.3.3.5.1 Brief overview, comments on data quality and technological maturity

Water electrolysis is a technology with a high degree of maturity.

The data on construction and operation were taken from the literature. There is considerable uncertainty about how the lifetimes of the electrolysers will develop.

5.3.3.5.2 Results

To make the following result diagrams more readable, the paths for hydrogen production are listed again in Table 27. Only the path numbers are then noted on the diagrams.

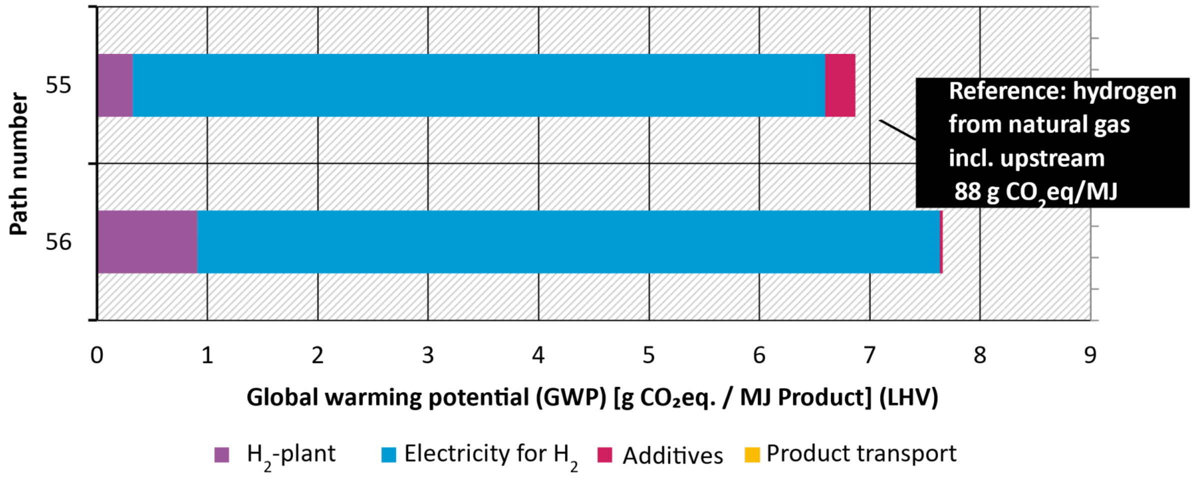
Table 29: Supply paths for hydrogen

Path	Location	Electrolysis	Power source	Transport
55	Germany	Alkaline electrolysis	Wind onshore	Gas grid
56	Germany	Polymer electrolyte membrane electrolysis	Wind onshore	Gas grid

5.3.3.5.2.1 Global warming potential today

Figure 54 shows the results for the global warming potential (GWP) of the hydrogen paths for the year 2015. The process steps broken down in the results are described in more detail in Table 15. Path 56, in which PEM electrolysis is used, is slightly worse. Compared with the reference, the production of hydrogen by steam reforming of natural gas (88 g CO_2eq/MJ product), however, both paths perform significantly better. This is also due to the power source used in this path (wind onshore). Electricity for electrolysis also contributes the largest share to the global warming potential in the production of hydrogen.

Figure 54: Global warming potential 2015 hydrogen supply paths (full load hours electrolysis)

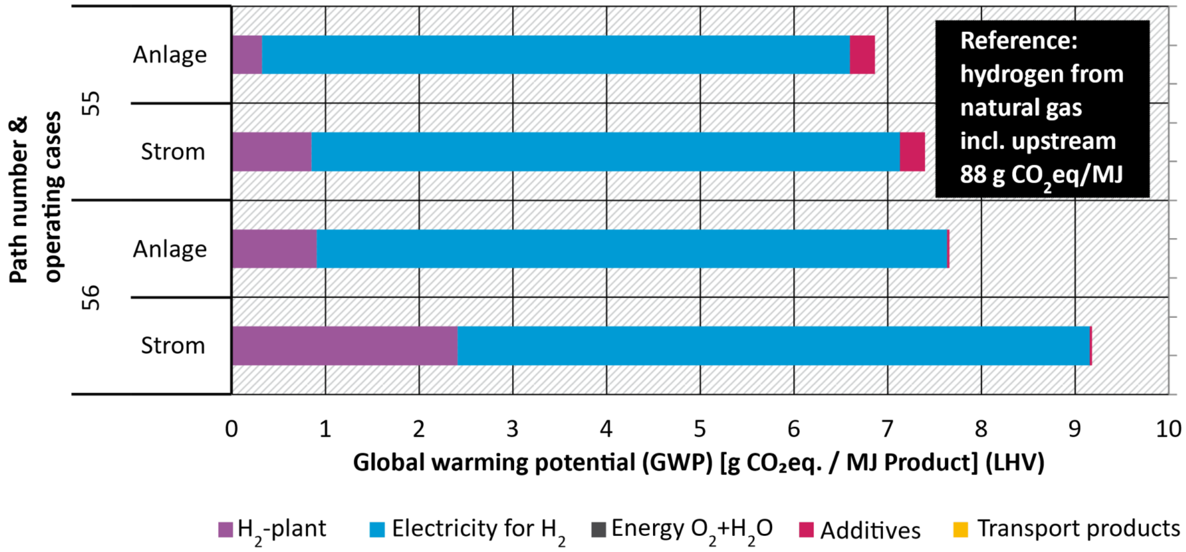


Source: own figure, ifeu

5.3.3.5.2.2 Second main case: global warming potential today depending on the mode of operation

As a second main case, the global warming potential of the hydrogen paths in 2015 is again calculated using the full load hours of the power source. This approximates the case where the electrolysers only run when electricity is available from the linked power source (see Chapter 5.1.3.2). Figure 55 shows the results of these LCA calculations.

Figure 55: Global warming potential 2015 hydrogen supply paths (full-load hours of electricity source)



Source: own figure, ifeu

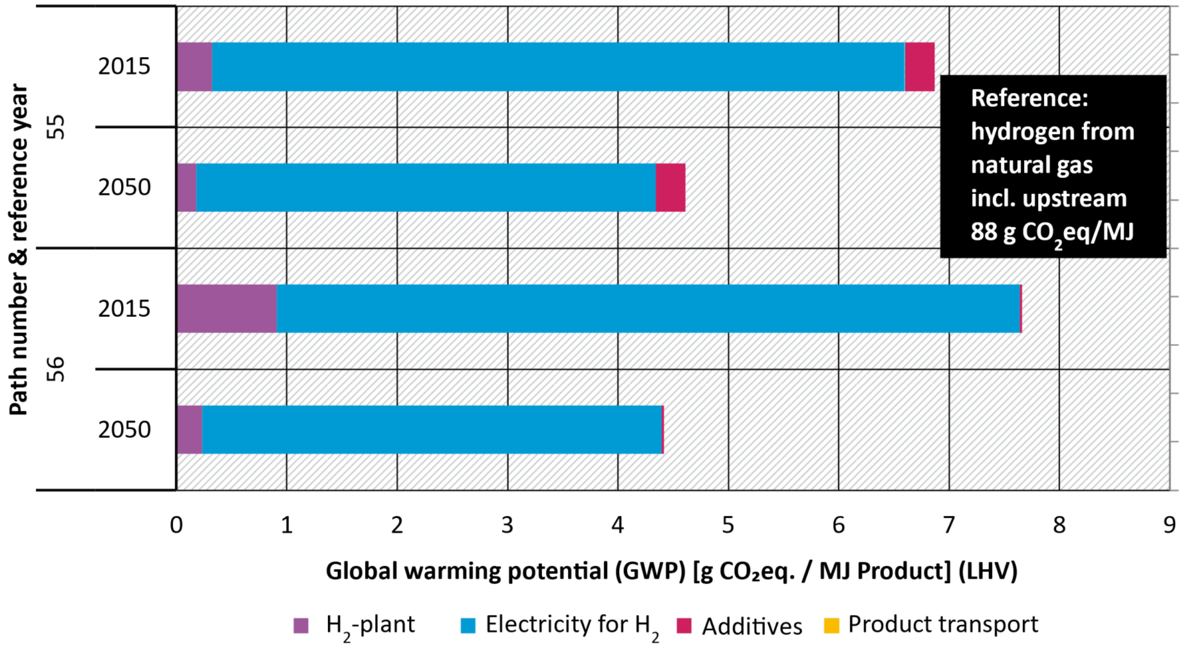
As with the other products, the global warming potential of both paths increases compared to the calculation with the electrolyser's full-load hours (Figure 54). The reason for this is the higher contribution of the plant infrastructure. The environmental impacts arising from the construction of these plants are distributed over a lower product output at lower full-load hours and the same service life.

For path 56 with PEM electrolysis, which today still has a shorter service life than alkaline electrolysis, the increase is more pronounced than for path 55. In the operating case "full load hours power source" the production of hydrogen here leads to a GWP of 9 g CO_2eq/MJ product, in the operating case "full load hours electrolyser" this is 7.5 g CO_2eq/MJ product. This corresponds to an increase of 17%.

5.3.3.5.2.3 Global warming potential 2050

Figure 56 compares the results for the global warming potential (GWP) of the hydrogen paths for the year 2050 with those for 2015. Compared with the results for 2015, the values have fallen by 33% (path 55) and 42% (path 56).

Figure 56: Global warming potential 2050 hydrogen supply paths (full-load hours electrolysis)



Source: own figure, ifeu

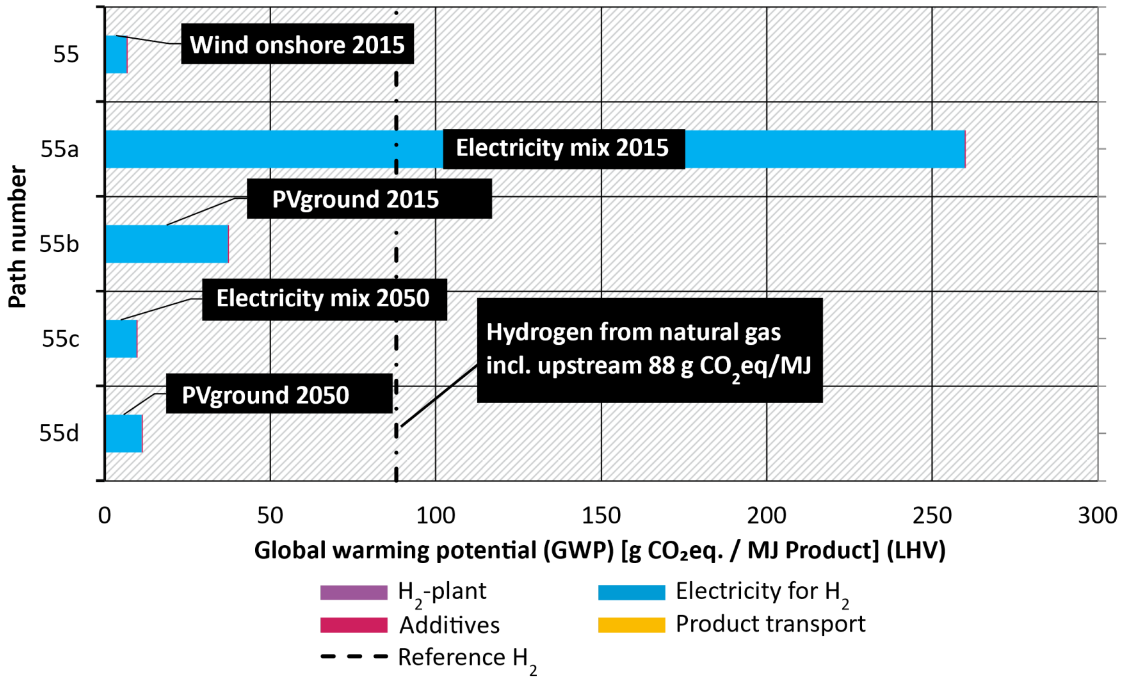
Both paths are in the range of 4.5 g CO_2eq/MJ product in 2050, which means a reduction of about 94% compared to hydrogen from fossil natural gas.

The decline is due to the lower global warming potential of wind power as a source of electricity; improved processes, higher secondary material quotas and the use of renewable energies in the production of e. g. steel, cement and silicon (Chapter 5.1.2) for the electricity generation plants are the reason for this. The increased efficiency of both electrolysis processes and the longer service life of PEM electrolysis also play a role.

5.3.3.5.2.4 Sensitivity: global warming potential 2015/2050 depending on the electricity source

The global warming potential of hydrogen path 55 (H_2, AEL, wind onshore) with electricity from PV ground-mounted systems and from the electricity mix is calculated as the sensitivity. Figure 57 shows the results of these LCA calculations.

Figure 57: **Sensitivity calculations for path 55 (hydrogen, AEL) with PV electricity and electricity mix 2015/2050 (full load hours electrolysis)**



Source: own figure, ifeu

For 2015, electricity purchased from ground-mounted PV systems (path 55b) means an increase in the GWP to 38 g CO_2eq/MJ hydrogen; with electricity from the electricity mix (path 55a), the GWP even increases to 260 g CO_2eq/MJ hydrogen. This is almost three times the reference value for hydrogen from natural gas. For the year 2050, the purchase of electricity from the mix (path 55c, 10 g CO_2eq/MJ hydrogen) is even an advantage over the pure use of photovoltaics (path 55d, 11 g CO_2eq/MJ hydrogen). In the basic version of path 55 with wind onshore, GWP in 2050 is around 7 g CO_2eq/MJ hydrogen.

5.3.3.5.2.5 Selected results in other impact categories

Table 30 shows the ranges of the results for all ten environmental impacts examined in this study for the hydrogen paths for the year 2050 with the full load hours of the synthesis plant. A detailed list for all paths, reference years and cases of operation can be found on the website of the Federal Environment Agency. A more detailed analysis of the causes (materials, procedures, processes) of the environmental impacts is given in Chapter 5.3.4 on cross-product analysis.

Table 30: **Ranges of the LCA results 2050 of the hydrogen paths (full-load hours synthesis plant)**

Environmental Impact	Reference	Min (path)	Max (path)	Comment
Global warming potential g CO_2 eq/MJ	88	4.4 (56)	4.6 (55)	
Acidification [g SO_2eq/MJ]	0.049	0.043 (56)	0.060 (55)	
Eutrophication [g PO_4eq/MJ].	0.0090	0.023 (56)	0.024 (55)	

Environmental Impact	**Reference**	**Min (path)**	**Max (path)**	**Comment**
Cumulative energy demand [MJ/MJ]	1.4	1.3 (56)	1.3 (55)	
Summer smog [g C_2H_4eq/MJ]	0.032	0.013 (56)	0.014 (55)	
Ozone depletion [g CFC11eq/MJ]	1.6E-05	5.0E-06 (55)	5.5E-06 (56)	
Particulate matter [g/MJ]	0.042	0.037 (56)	0.047 (55)	
Cumulative raw material demand [kg/MJ]	0.038	0.028 (56)	0.030 (55)	
Land use [m^2a/MJ]	7.5E-08	3.9E-04 (56)	3.9E-04 (55)	
Water demand [l/MJ]	0.048	0.14 (56)	0.14 (55)	

As described in Chapter 5.3.3.5.2.3 the values for **global warming potential** are 4.4 and 4.6 g CO_2 eq/MJ. This corresponds to about 5% of the fossil reference (of the average global warming potential of hydrogen from natural gas, including the upstream chain). Path 56 with PEM electrolysis performs slightly better than path 55 with alkaline electrolysis, in which the production of the electrolyte contributes. The main source is the electricity generation for electrolysis (here wind onshore).

For **acidification** the values are 0.043 and 0.060 g SO_2eq/MJ. This corresponds to 88, or 122% of the fossil reference. Here, too, path 56 (PEM) performs slightly better than Pfad 55 (AEL), where the construction and operation of the electrolyser make a larger contribution. However, the main source in both paths is the generation of electricity for the electrolysis.

For **eutrophication** the values are 0.023 and 0.023 g PO_4eq/MJ. This corresponds to about 260% of the fossil reference. Here too, the main source is electricity generation for electrolysis.

The **cumulative energy demand** in both paths is 1.3 MJ/MJ. This corresponds to about 90% of the fossil reference. Here too, the main cause is electricity generation for electrolysis.

For the impact category **summer smog** the values are 0.013 and 0.014 g C_2H_4eq/MJ. This corresponds to about 40% of the fossil reference. Here, too, path 56 (PEM) performs slightly better than path 55 (AEL), where the construction and operation of the electrolyser make a larger contribution. However, the main source in both paths is the generation of electricity for the electrolysis.

For **ozone depletion**, the values are 5.0E-06 and 5.5E-06 g CFC11 eq/MJ. This corresponds to about 10% and 20% of the fossil reference. Again, path 55 (AEL) performs slightly better than path 56 (PEM), where the construction and operation of the electrolyser makes a larger contribution. However, the main source in both paths is the generation of electricity for the electrolysis.

For the impact category **particulate matter,** the values are 0.037 and 0.047 g/MJ. This corresponds to about 30% of the fossil reference. Again, path 56 (PEM) performs better than path 55 (AEL), in which the construction and operation of the electrolyser make a larger contribution. However, the main source in both paths is the generation of electricity for the electrolysis.

The **cumulative raw material demand** is 0.028 and 0.030 kg/MJ. This corresponds to around 75% of the fossil reference. The main cause in both paths is again electricity generation for electrolysis.

In terms of **land use,** the value for both paths is 3.9E-04 m^2a/MJ. This corresponds to about 520,000% of the fossil reference. The main cause in both paths is again electricity generation for electrolysis (here wind onshore).

The **water use** is 0.14 l/MJ. This corresponds to around 290% of the fossil reference. In both paths, the main causes are electricity generation for electrolysis and process water uses.

5.3.4 Cross-product analysis

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 e.g., 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 carriers. Environmental impacts resulting from incineration, which differ from product to product are 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).

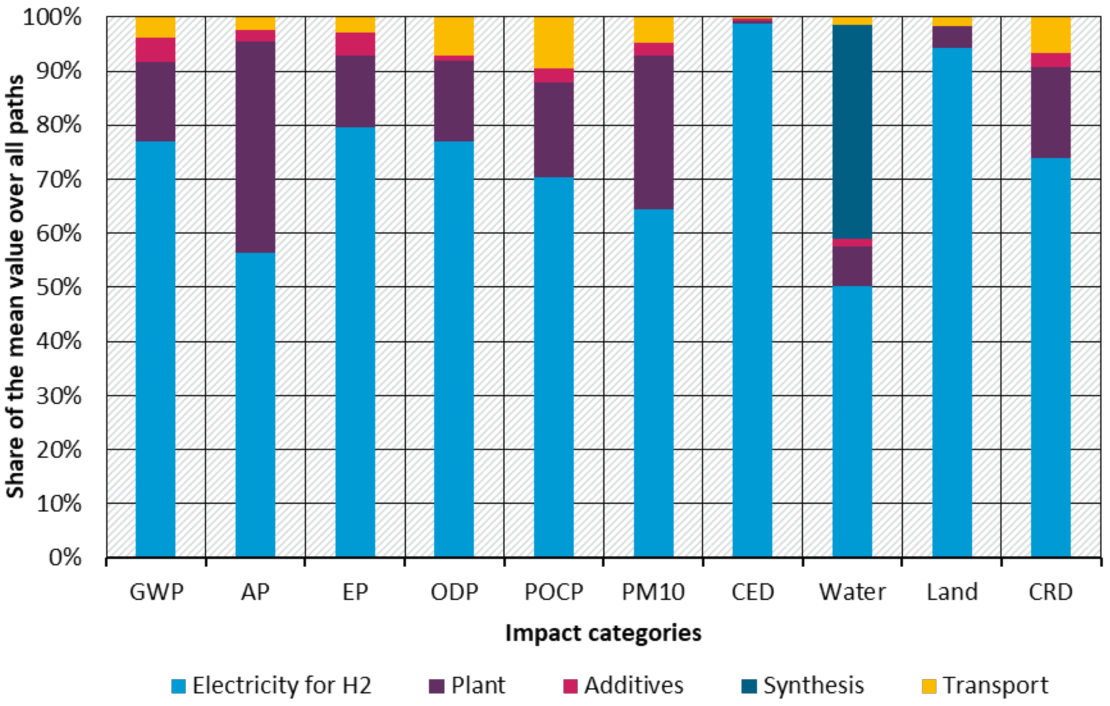
In Chapter 5.3.4.1 a dominance analysis identifies the contributions of the individual process steps of the supply paths (e.g., electricity generation, construction of synthesis plants, transport) to all environmental impacts for the year 2050. In addition, it is analysed which materials (e.g., steel, cement) are responsible for the environmental impacts in 2050 through their manufacturing processes.

Chapter 5.3.4.2 then shows how the supply paths in the individual impact categories can be standardised by comparing them with current emissions and demand in Germany. Finally, Chapter 5.3.4.3 analyses the ranges of LCA results for all impact categories and energy carriers.

5.3.4.1 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 58 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 58: Dominance analysis of all environmental impact categories for the medians over all fully electricity-based supply paths in 2050 (full-load hours of synthesis plant)

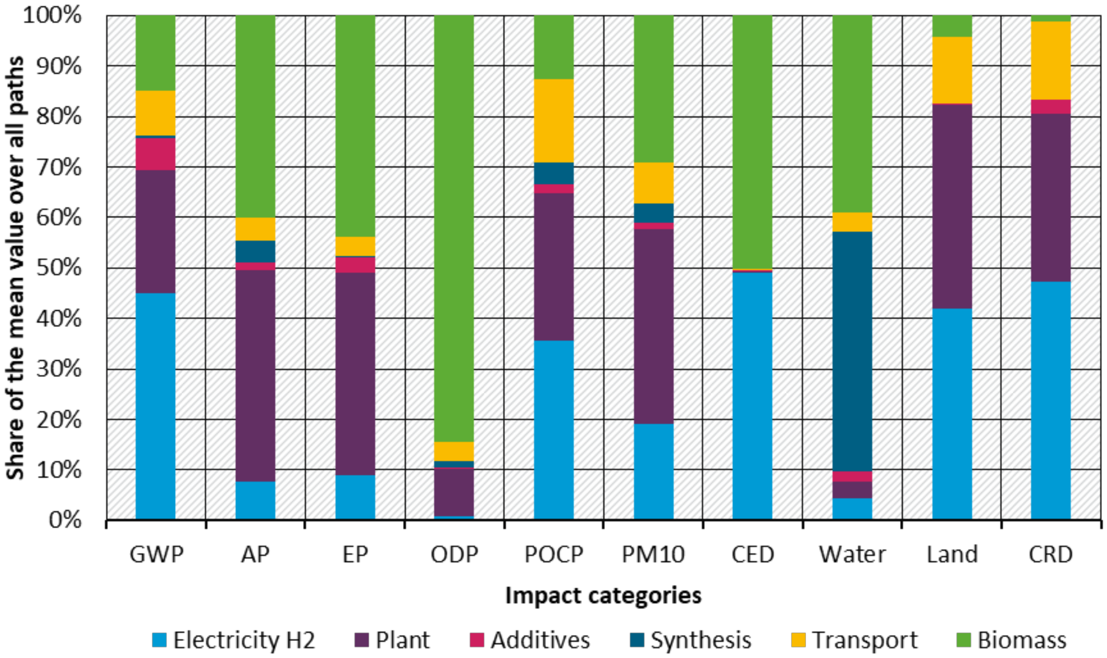


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

It can be seen – as in the product-related analysis in Chapter 5.3.3– that in 2050 the generation of electricity for electrolysis and the construction of synthesis and separation plants via 90% contribute to almost all impact categories. The exception is water consumption, where the direct process water demand, averaged over all fully electricity-based paths, contributes about one third. To a lesser extent, transport infrastructure (pipelines, ships, trucks, etc.) and direct emissions from transport contribute across all impact categories.

Figure 59: 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 59 shows the dominance analysis for all impact categories – averaged over all supply paths in which biogenic residues and cultivation biomass are used – for the year 2050. The use of electricity for electrolysis in the PBtL 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 carriers (biomass gasification) make relevant contributions to acidification, ozone depletion and photochemical ozone creation potential, as well as to secondary particulate matter formation.

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

- The production and operation of electricity generation facilities:
  - The most important materials for wind power plants are steel and glass fibre reinforced plastics (GRP); the production of aluminium, copper, cement and transport for plant construction are also relevant.
  - 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) power plants with liquid salt heat storage use nitrate salts as storage medium, which cause significant N_2O emissions during production.

- The manufacture and operation of other 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 carriers – 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, v. a. NH_3, N_2O and nitrate, contribute most. In addition, there are the direct emissions from the transport of biomass.

5.3.4.2 Normalisation

Chapter 5.3.3 showed that the production of synthetic energy carriers is usually associated with a lower global warming potential than that of fossil reference products. In many other impact categories, however, synthetic energy carriers perform significantly worse than the reference. The ranges of results for the individual products are shown in tables in the respective subchapters of Chapter 5.3.3 (e.g., for fully electricity-based Fischer-Tropsch fuel in Table 18) and in the diagrams in the following Chapter 5.3.4.3

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

In this study, the starting point for normalisation 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 relief 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.

The following text box describes the normalisation exemplary for the supply path 10 (FT fuel, production in Germany, CO_2 from the air, PV ground installation, alkaline electrolysis).

Examplary normalisation of environmental impacts for path 10 in 2050

The global warming potential of a Fischer-Tropsch fuel from supply path 10 (production in Germany, CO_2 from the air, PV ground installation, alkaline electrolysis) in the year 2050 is 22 g CO_2eq/MJ in the operating case "full load hours synthesis plant". For the fossil reference mix this value is 85 g CO_2eq/MJ. If the fossil reference fuel is replaced by the synthetic one, 63 g CO_2eq per megajoule are avoided.

The acidification potential of the same Fischer-Tropsch fuel from supply path 10 in 2050 is 0.21 g SO_2eq/MJ. For the fossil reference mix this value is 0.056 g SO_2eq/MJ. If the fossil reference fuel is replaced by the synthetic one, an additional 0.15 g SO_2eq per megajoule are released.

In 2016, the global warming potential of all emissions in Germany (i.e., not only those caused by fuel) was 909 million tonnes CO_2eq and the acidification potential of all emissions was around 2.65 million tonnes SO_2eq. The calculated relief and pollution from Fischer-Tropsch fuel from supply path 10 are normalised to these emissions:

Global warming potential: -63/909 = -0.069
Acidification potential: +0.15/2.65 = +0.057

In a final step, these quotients are scaled to that of the global warming potential:

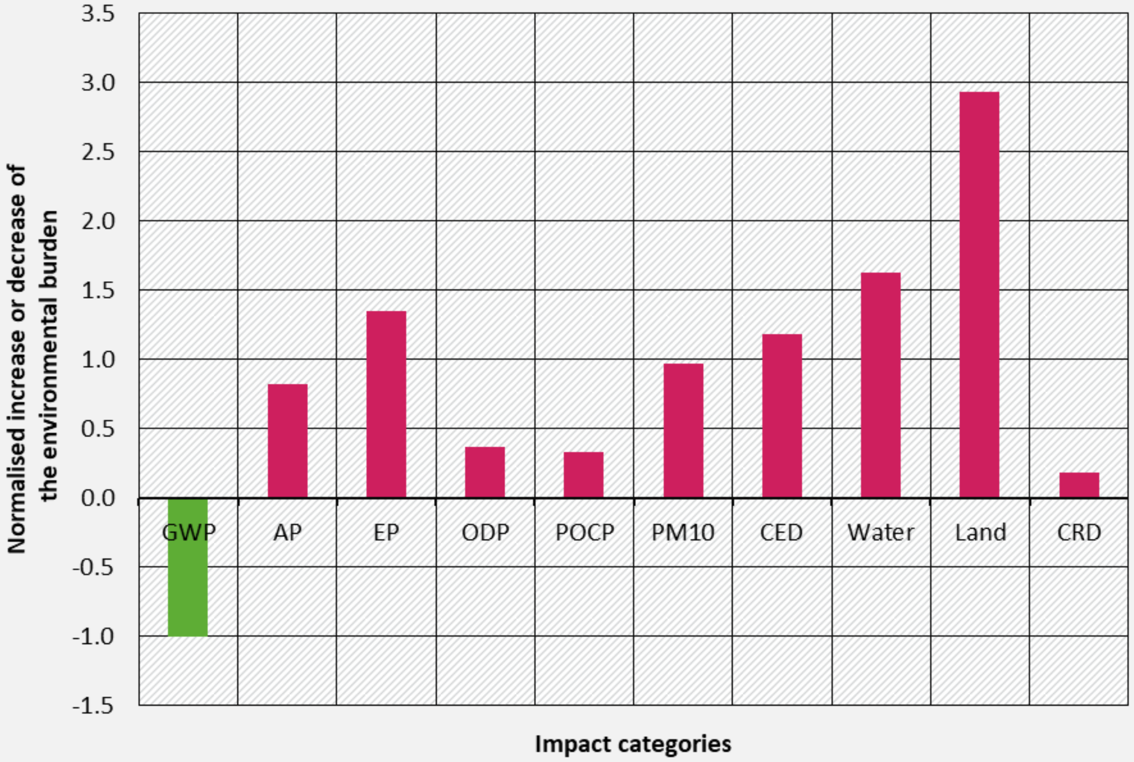
Global warming potential: -0.069/0.069 = -1
Acidification potential: 0.057/0.069= + 0.83

What initially looks like an abstract calculation has a concrete meaning: the normalised quotient of the acidification potential puts the additional burdens in this impact category in a directly proportional relationship to greenhouse gas reduction. Statements such as the following are now possible: "If enough Fischer-Tropsch fuel (from path 10) is produced in 2050 so the avoided amount of CO_2 equivalents is x% of all GHG emissions in 2016, the additional acidification will be 0.83 times x% of the acidification in 2016".

An example with fictitious numbers: assuming that in 2050 50 billion litres of Fischer-Tropsch fuel (from path 10) will be produced and used. Then 98.3 million tonnes of CO_2eq will be avoided compared to the fossil reference. This is around 11% of all GHG emissions in Germany in 2016. We know from normalisation that simultaneously acidifying emissions in the order of 11 x 0.83 = 9% of 2016 emissions are produced. The relief in the GWP is therefore associated with a burden in the acidification potential of a similar order of magnitude.

Figure 60 shows this normalisation of all environmental impacts of path 10.

Figure 60: **Calculated increase or decrease of the environmental burdens in 2050 by Fischer-Tropsch fuel from path 10 (CO_2 from the air, PV ground-mounted system in Germany)**

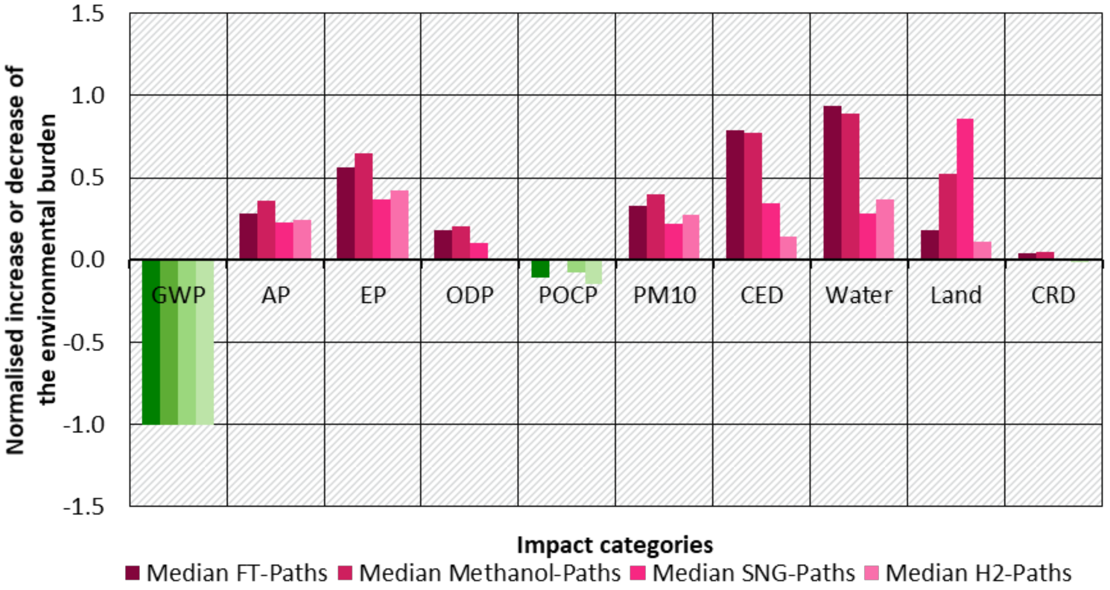


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

In 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 formed, then, as in the calculation example, these were 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 61: **Calculated increase or decrease of the environmental 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 61 the increases and decreases 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 pressures 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.

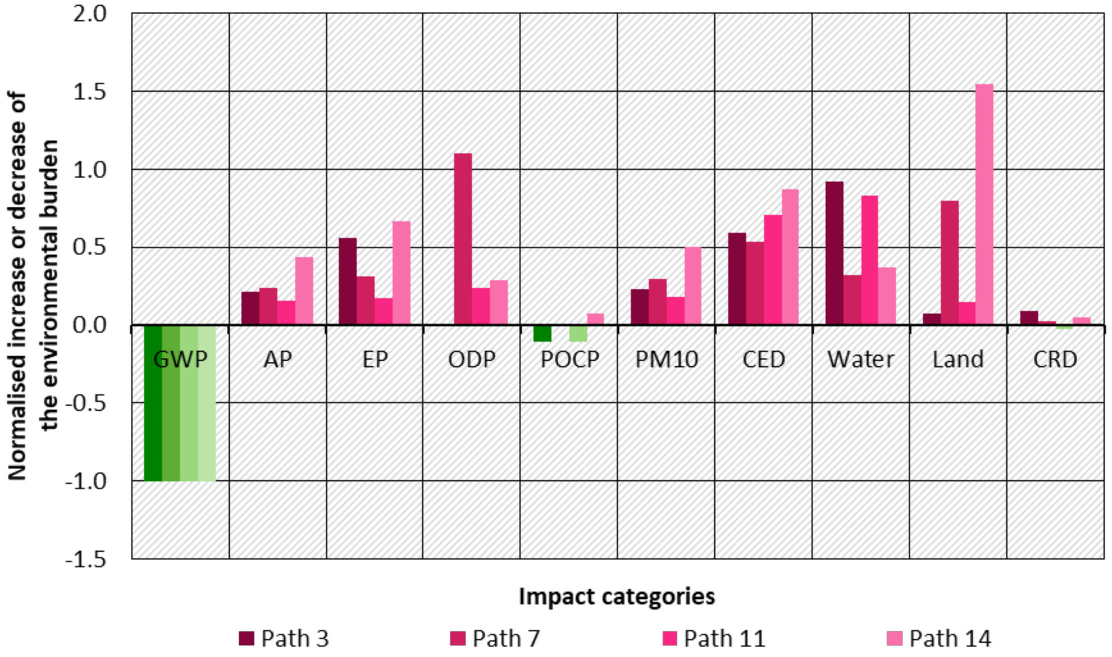
The median values for synthetic natural gas (SNG) follow a similar pattern but are better than those for Fischer-Tropsch fuels and methanol for almost all categories. The hydrogen paths perform similarly to SNG in this analysis but are significantly better in the "land" category.

However, the selection of paths shown in chapter 5.2 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 land use. 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 carriers 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 in Figure 62 to Figure 64 for Fischer-Tropsch fuels.

Figure 62: **Calculated increase or decrease of the environmental burdens in 2050 compared to fossil fuels, normalised to the situation in 2016 for fully electricity-based FT-paths (full-load hours synthesis plant)**

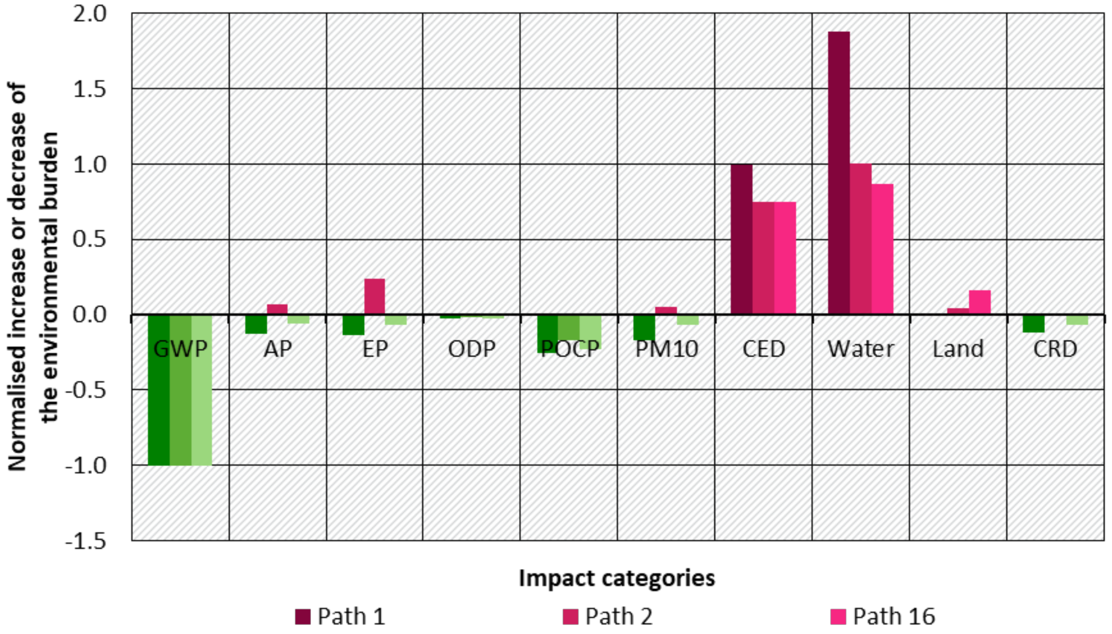


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

Figure 62 shows the normalised increases and decreases 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 61. 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 63: **Calculated increase or decrease of the environmental burdens in 2050 compared to fossil energy carriers, normalised to the situation in 2016 for FT-paths with bio-residuals**

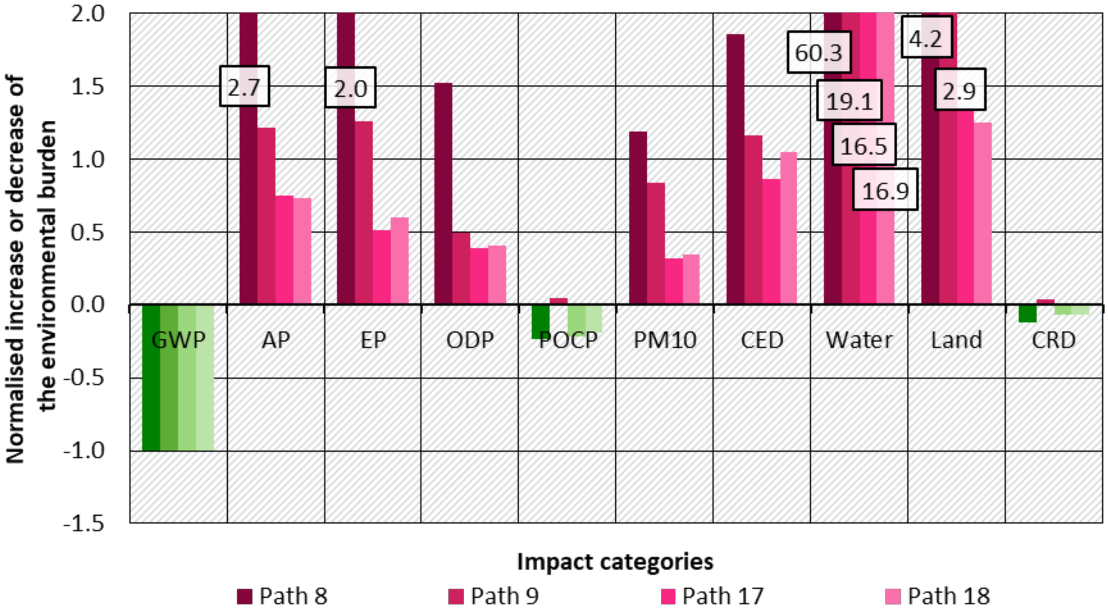


GWP: Global warming potential, AP: Acidification, EP: Eutrophication, ODP: Ozone depletion, POCP: Summer smog, PM_{10}: Particulate matter, CED: Cumulative energy demand, Water: Water consumption, Land: Land use, CRD: Cumulative raw material demand

Source: own figure, ifeu

Figure 63 shows the normalised increases and decreases 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 contribute no environmental burdens from cultivation in accordance with the LCA convention. This is why most environmental categories show a decrease compared to the production of fossil fuels. In future, this allocation and thus the LCA assessment could change (see "Limitations of the LCA approach" in Chapter 5.3.5.1)

Figure 64: **Calculated increase or decrease of the environmental burden in 2050 compared to fossil energy carriers, 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

Figure 64 shows the normalised increases and decreases for four paths in which Fischer-Tropsch fuel is produced from poplar wood from short rotation coppices (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.

5.3.4.3 Analysis of the individual impact categories

This chapter shows the ranges of the energy-related environmental impacts for all products, different groups of supply paths, the reference years 2015 and 2050 and the two cases of operation (Figure 66 to Figure 74). The environmental impacts of the paths in which the electricity mix is used are marked separately. In addition, the respective environmental impacts are shown for the fossil reference (petrol/diesel, methanol, natural gas, hydrogen from natural gas). The values can be read off the left-hand axis.

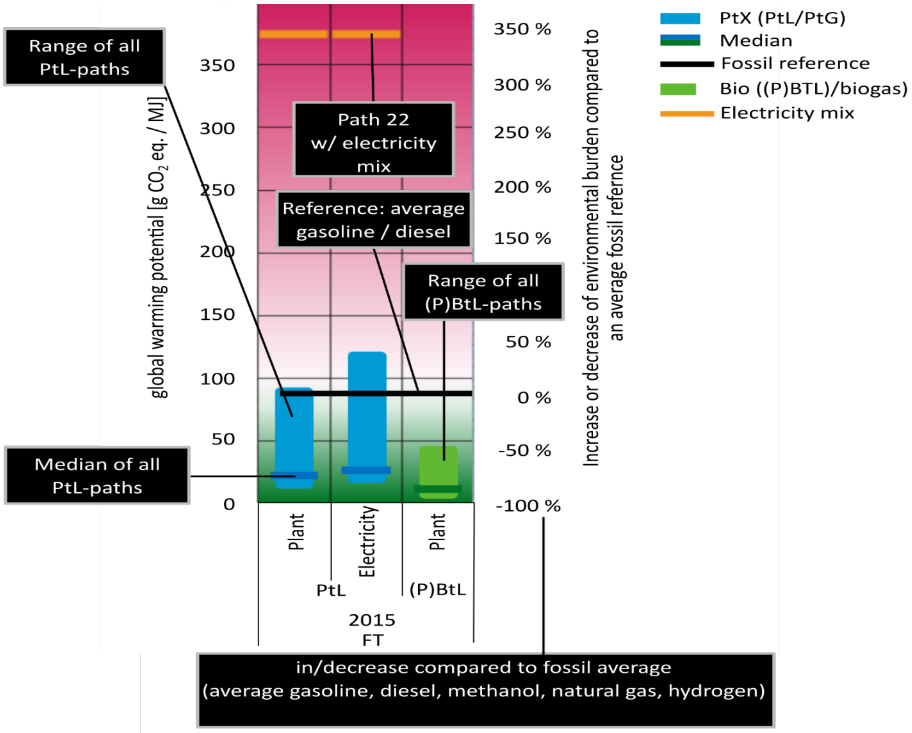
On the right-hand axis, the relative burden or relief in % compared to an average fossil fuel (arithmetic mean of the environmental impacts of the production of petrol, diesel, methanol, natural gas and hydrogen from natural gas) is plotted. The formation of the mean value is necessary here so that the scale shown applies equally to all product groups. In addition, the background of the diagram is coloured red (additional load) and green (additional relief) in order to be able to quickly classify the results.

The terms "plant" and "electricity" designate the mode of operation of the synthesis plant – according to possible full load hours of the synthesis plant or the electricity generation for electrolysis (5.1.3.2). Put simply, in the "full-load hours power source" mode of operation, the environmental impacts of the construction of electrolysers, synthesis and deposition plants increase, since these are distributed over fixed lifetimes to the quantities of energy carriers produced during this time. If the plants run for shorter periods of time each year, fewer energy carriers are produced, which then receive a larger "backpack" of environmental impacts per unit from the construction of the plant.

For 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.

As in Chapter 5.3.3the supply paths for liquid energy carriers are grouped according to fully electricity-based PtL paths and biomass-based (P)BtL paths. The reasons for this are that the (P)BtL processes have a different level of technological maturity and, in addition, operation of the plants only at the full load hours of the power source is not to be expected. For each product group shown, the median of all results of this group is also shown. As a reading example, the various elements of the diagram for the global warming potential 2015 for Fischer-Tropsch fuels are labelled in Figure 65

Figure 65: Exemplary figure: global warming potential ranges 2015 for Fischer-Tropsch fuels and potential increase or decrease of impact compared to a fossil reference



Source: own figure, ifeu

As everywhere in the report, the results for the reference year 2030 have been omitted to keep the figures as clear as possible. A complete list of all results can be found on the Federal Environment Agency's website.

5.3.4.3.1 Global warming potential

Figure 66 shows the ranges of the global warming potential for all products. The results are divided into path groups according to electricity and biomass input. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, the ranges reach up to 95% below the fossil reference. However, especially for 2015, there are also paths for all energy carriers 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 (Chapter 5.3.2). In this case, the production of synthetic energy carriers has a global warming potential of around 350% of the fossil reference product.

In 2015, **fully electricity-based** PtL energy carriers (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 biomass-based liquid energy carriers (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 ranges 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 biomass-based products, the main sources of the global warming potential are the cultivation and transport of the biomass and, in the PBtL paths, the electricity for electrolysis.

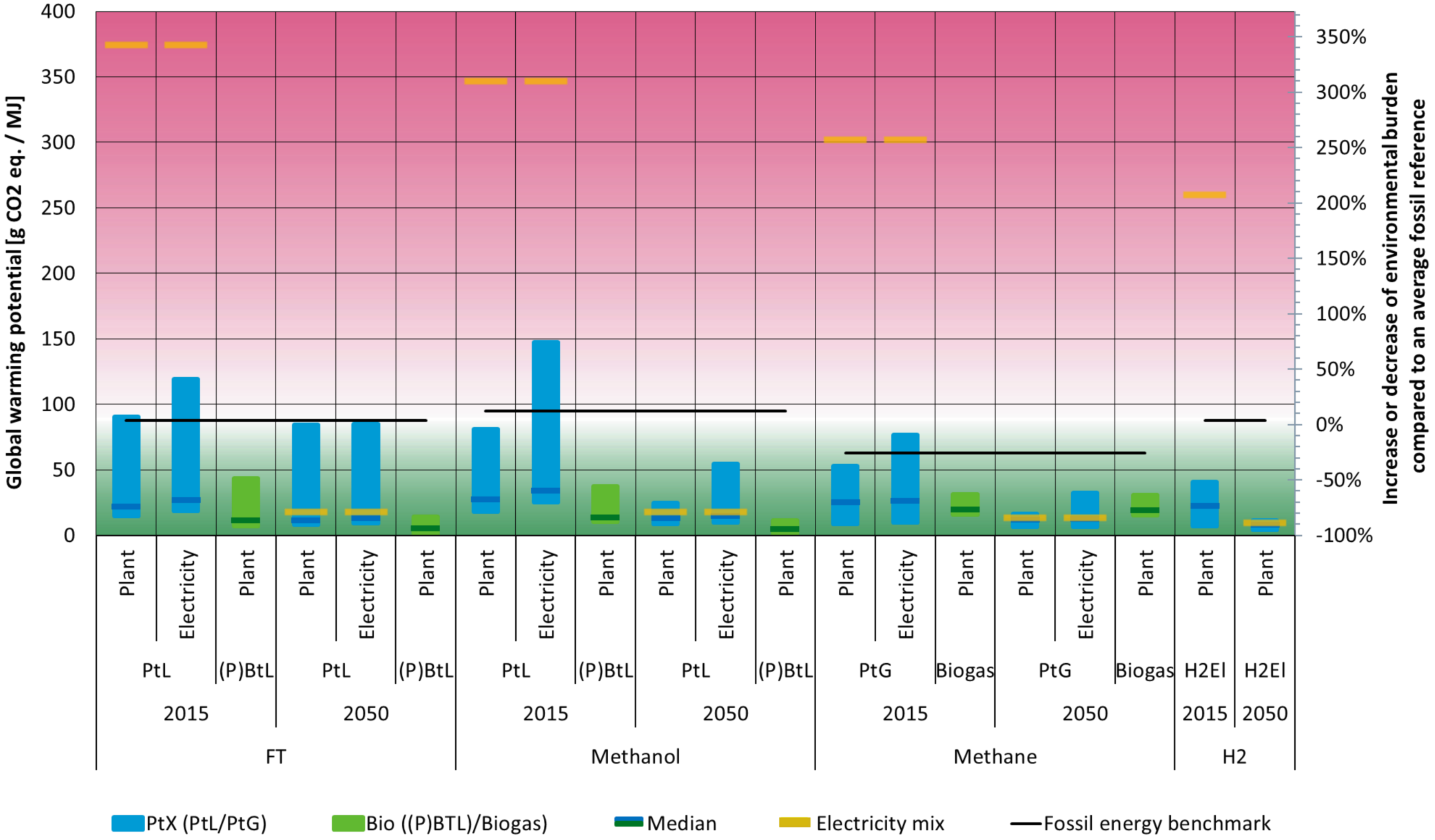
In 2050, results will improve for almost all products and cases of operation. This is mainly due to the decreasing greenhouse intensity of electricity for electrolysis. The materials used in the construction of the electricity generation, synthesis and separation plants (steel, concrete, aluminium, copper) are responsible for lower emissions due to changes in production processes (Chapter 5.1.2). In addition, the use of synthetic energy carriers reduces the greenhouse gas emissions from the transport of the products. For the FT fuel, the global warming potential of the least favourable path (path 61) decreases less, since in this path the CO_2 use from a lignite-oxyfuel power plant is attributed entirely to the FT fuel (Chapter 5.1.3.4).

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

To keep the global warming potential of the energy carriers 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" case 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 cases of operation will be less significant. In terms of global warming potential, it will then be easy to use the general electricity mix.

Figure 66: **Global warming potential – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference**



Source: own figure, ifeu

5.3.4.3.2 Acidification potential

Figure 67 shows the ranges of the acidification potential for all products. The results are divided into path groups according to electricity and biomass input. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – are above the fossil reference. However, the extreme values in this impact category are very far apart. While the production of FT fuel with electricity and CO_2 from geothermal energy in Iceland for the reference year 2015 is about 11,000% above the acidification potential of the average fossil reference, the most favourable path (56, H_2, wind onshore, PEM) in 2050 is about 25% below.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of results, while electricity-based methane (SNG) and hydrogen perform significantly better. This is also the case if the very unfavourable paths 15 and 37 (geothermal energy in Iceland) are excluded from the calculation. Then the worst path for FT fuel (path 10, PV in Germany, DAC) is still at around 1,800%, the worst path for methanol (path 32, PV in Germany, DAC) at around 2,100% and the worst path for synthetic natural gas (path 48, PV in Germany, DAC) at around 1,300% of the average fossil reference. Paths using the general electricity mix are also among the three worst paths for all products in 2015.

For all electricity-based products, the main source of acidification potential is the electrolysis power generation plants – especially via the processes and materials described in Chapter 5.3.4.1. However, the construction of electrolysers, synthesis and capture plants plays a greater role in acidification than in global warming potential. In the case of paths with CO_2 capture from the air, all facilities together can even contribute up to 60%.

The biomass-based, liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) perform significantly better than the fully electricity-based ones at first glance – both in terms of the lowest acidification potential of the favourable paths and the emissions of the least favourable paths. If the extremely unfavourable paths 15 and 37 (FT fuel and methanol with electricity from geothermal energy in Iceland) are taken out of the comparison, the paths with cultivated biomass are among the worst. Paths 8 and 30 (FT fuel and methanol from BtL synthesis with wood from short-rotation plantations) then even show an acidification potential in 2050 that is two to three times higher than the worst electricity-based paths 10 and 32 (FT fuel and methanol with PV electricity in Germany and DAC). Supply paths with biogenic residues perform best. This trend was already evident in Chapter 5.3.4.2.

With methane, the advantage of biogas over SNG is not quite as great.

The main sources of acidification potential for all biomass-based products are the cultivation and transport of the biomass and, in the PBtL paths, also the electricity for electrolysis. In the case of biomethane, the plant-internal provision of heat and electricity via NO_x emissions from the biogas CHP makes the greatest contribution to the acidification potential. This contribution is more pronounced in the biomethane paths with amine scrubbing due to the higher energy demand.

In 2050, results will improve for almost all products and cases of operation. This is mainly due to the decreasing acidification potential of electricity and plant production, and the higher efficiency of hydrogen electrolysis. The materials used in the construction of the electricity generation, synthesis and capture plants (especially copper, steel and aluminium) are responsible for lower emissions due to modified production processes and the use of renewable energy carriers (Chapter 5.1.2).

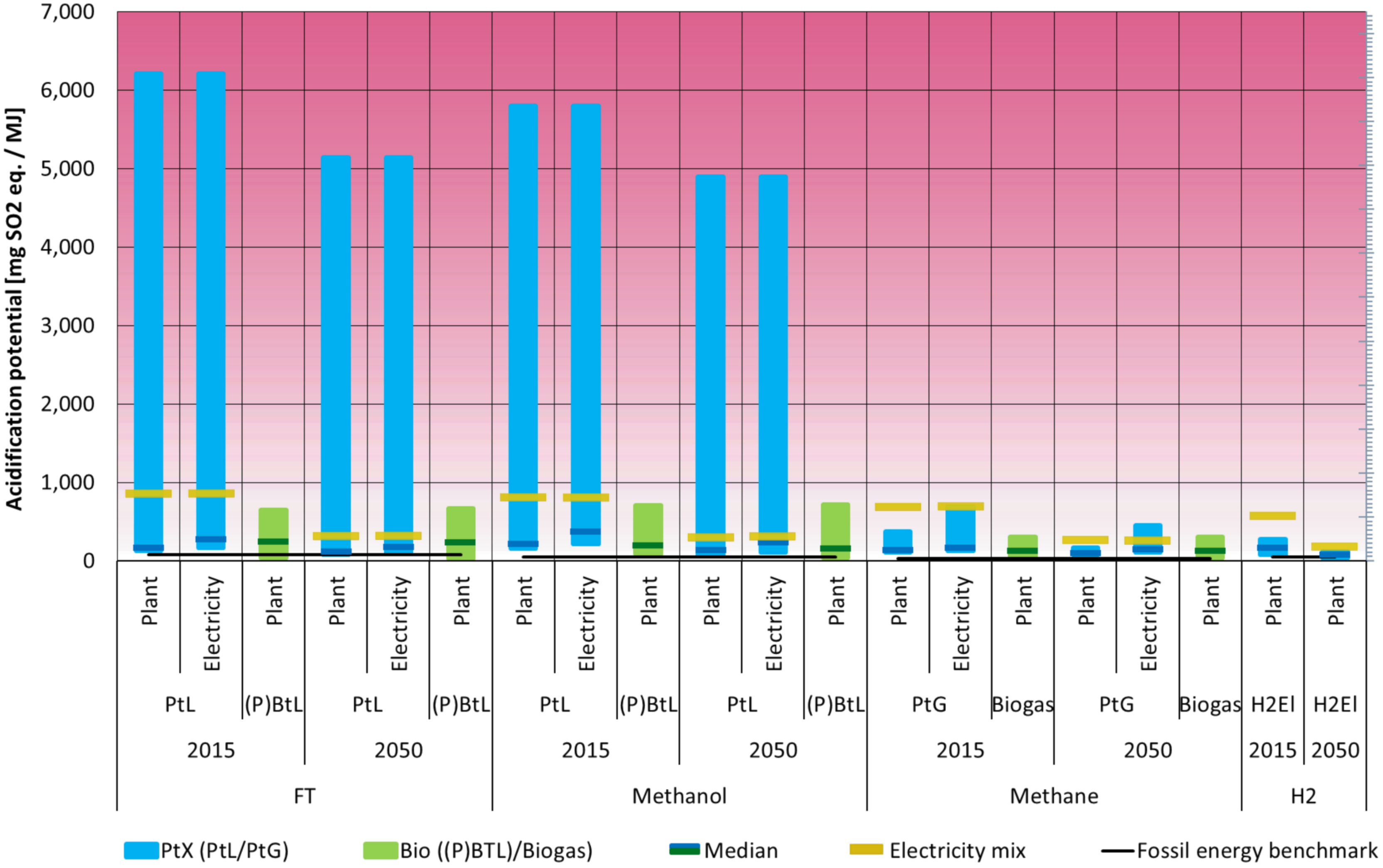
For the least favourable paths with electricity and CO_2 from geothermal energy in Iceland, the acidification potential decreases only slightly, as H_2S emissions from the power plant do not change. Only the efficiency of CO_2 capture improves slightly.

For the biomass-based products there is almost no improvement, as the main causes – cultivation and transport of the biomass and energy supply in the biogas plant – do not change. They are about four times larger than their fossil reference.

Averaged over all supply paths, SO_2 contributes 56%, NOx 22% and NH_3 15% to the specific acidification potential in 2050, and H_2S 4%.

The differences in the results for the operating cases "plant" and "electricity" are not apparent for the FT products and methanol paths in the diagram. In both categories, the paths with geothermal energy as the electricity source have the maximum values, which do not change with the operating case. For most other paths, the results for the operating case "full load hours power source" are about 150% of the operating case "full load hours synthesis plant".

Figure 67: Acidification potential – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



Source: own figure, ifeu

5.3.4.3.3 Eutrophication

Figure 68 shows the ranges of the eutrophication potential for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. The extreme values are also very far apart in this impact category. While the production of methanol with CO_2 capture from the air and electricity from PV in Germany (path 32) in 2015 in the electricity operating case leads to a calculated load of more than 4,000% of the average fossil reference, the most favourable path 1 (FT-BtL from straw in Germany) shows a relief of around 75% in 2050.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of results, with methanol performing slightly worse. This is because the synthesis plant makes a larger contribution and less heat can be extracted from the methanol synthesis and used in CO_2 capture. Electricity-based methane (SNG) and especially hydrogen perform significantly better than liquid energy carriers.
The paths with the use of the general electricity mix in 2015 are close to the medians for all predominantly electricity-based products.

The main source of eutrophication potential for all electricity-based products is electricity for electrolysis and, in the methanol paths, also for CO_2 capture – in each case via the processes and materials described in Chapter 5.3.4.1However, the construction of electrolysers, synthesis and capture plants plays a greater role in acidification than in global warming potential. In the case of paths with CO_2 capture from the air, all plants together can even contribute up to 60% – especially in the "full-load hours power source" mode of operation.

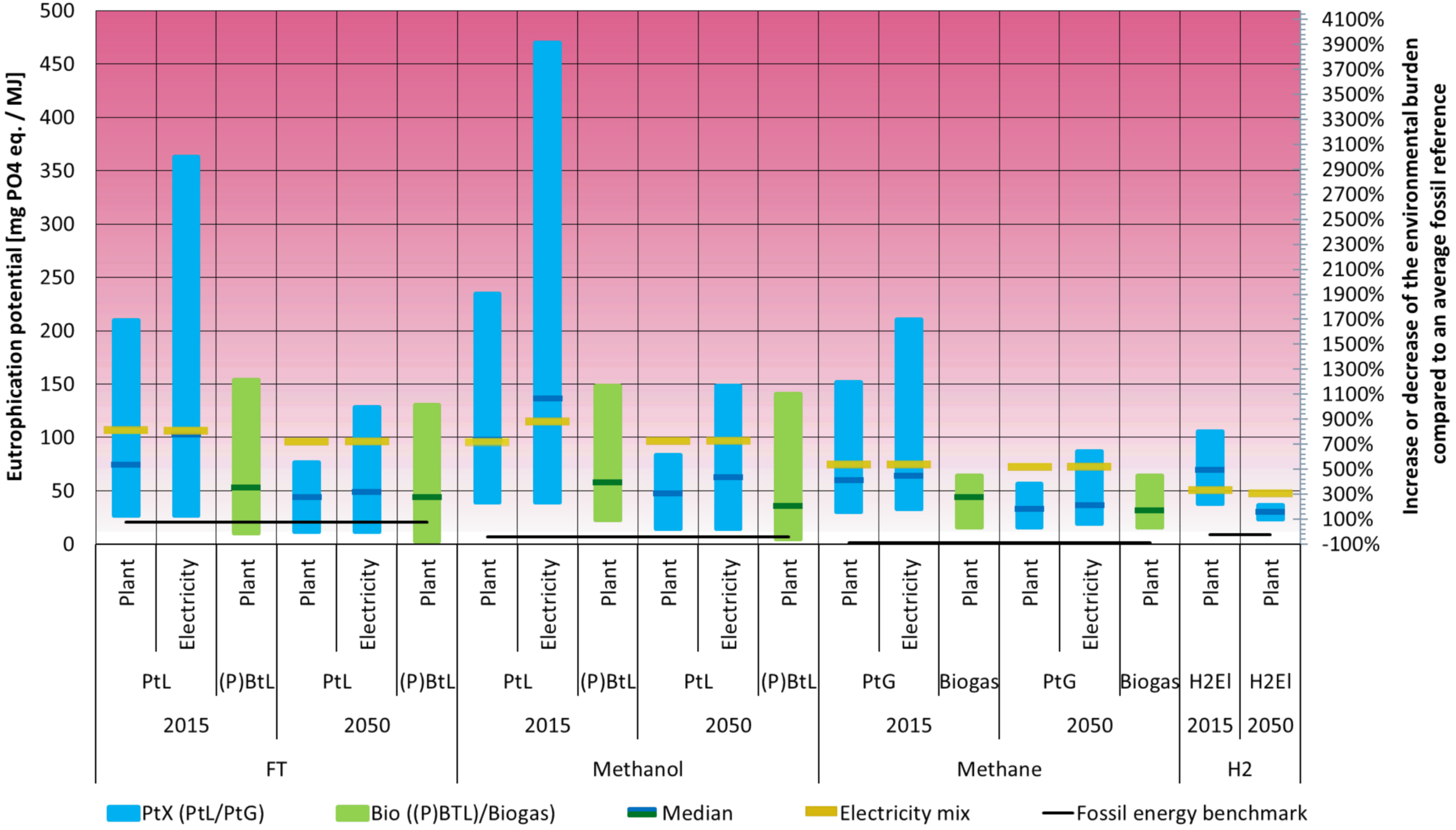
In 2015, the biomass-based energy carriers (FT fuel and methanol from (P)BtL syntheses, biogas) will perform better in terms of their eutrophication potential than the fully electricity-based ones – both in terms of the respective maximum and minimum values of the ranges of the supply paths. For all biomass-based products, the main sources of eutrophication potential are the cultivation and transport of biomass and, in the PBtL paths, electricity for electrolysis. In the case of biomethane, the greatest contribution to the eutrophication potential is made by the internal provision of heat and electricity via NO_x emissions from the biogas CHP. This contribution is more pronounced in the biomethane paths with amine scrubbing due to the higher energy demand.

In 2050, results will improve for almost all products and cases of operation. This is mainly due to the decreasing eutrophication potential of electricity and plant production. The materials used in the construction of the electricity generation, synthesis and capture plants (especially steel, copper and aluminium) are responsible for less eutrophicating emissions due to changes in production processes (Chapter 5.1.2). For the biomass-based products there is almost no improvement, since the main causes – cultivation of the biomass and energy supply in the biogas plant – do not change.

In 2050, PO_4^- with 54%, NH_3 with 23% and NOx with 17%, averaged over all supply paths, will contribute to the eutrophication potential.

The differences in the results for the operating cases "full-load hours synthesis plant" and "full-load hours power source" are proportionally similar in 2050 to 2015, due to the reduced eutrophicating emissions from the production of the materials used to build the power generation, synthesis and separation plants.

Figure 68: Eutrophication potential – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.4 Summer smog

Figure 69 shows the ranges of summer smog potential for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, depending on the path group, both additional burdens and relief are recorded compared to the average fossil reference. The extreme values in this impact category are also very far apart. While the production of methanol with CO_2 capture from the air and electricity from PV in Germany (path 32) in the "full-load hours power source" mode of operation will lead to a calculated burden of more than 850% of the average fossil reference in 2015, the most favourable path (path 1, FT-BtL from straw in Germany) will show a relief of around 98% in 2050.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of results, with methanol performing slightly worse. The reasons for this are that less heat can be extracted from methanol synthesis and used in CO_2 capture, and that more emissions per megajoule of product are produced due to the lower energy density when methanol is transported. Electricity-based methane (SNG) and hydrogen perform slightly better than liquid energy carriers. The paths using the general electricity mix are by far the worst in 2015 for almost all products – with the exception of path 32 (methanol, DAC, PV in "full load hours power source" case).

For all electricity-based products, the main source of summer smog potential is electricity for electrolysis and, in the methanol paths, also for CO_2 capture – in each case via the processes and materials described in Chapter 5.3.4.1However, the construction of the electrolysers, synthesis and separation plants plays a greater role in the summer smog potential than in the global warming potential. In the case of paths with CO_2 removal from the air, all plants together can even contribute up to 50% – especially in the "full-load hours power source" operating case.

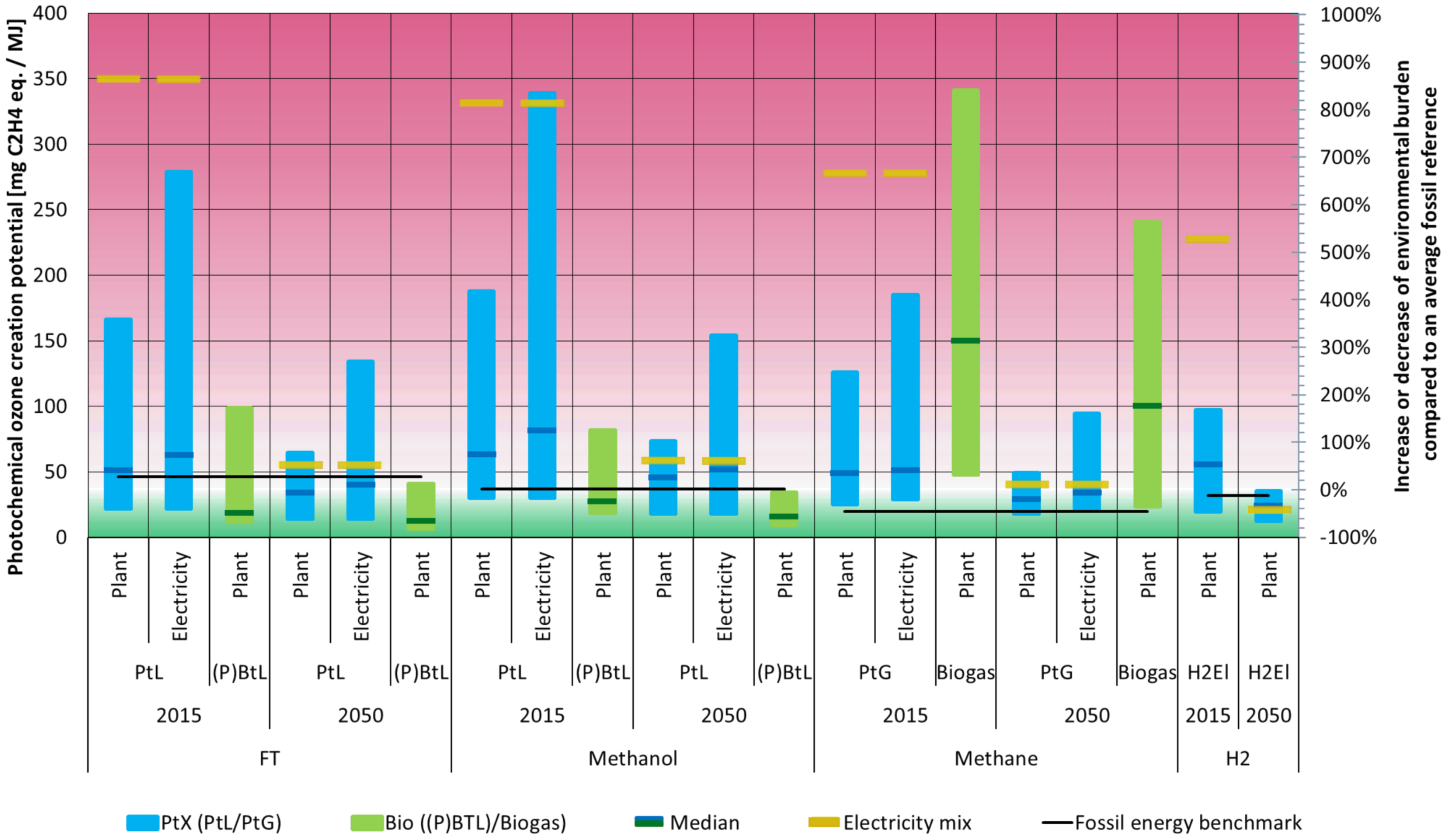
In 2015, the biomass-based liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will perform significantly better in terms of their summer smog potential than the fully electricity-based ones – both in terms of the respective maximum and minimum values of the ranges of the supply paths. However, biomethane shows significantly worse results than electricity-based methane. The main sources of summer smog potential for all biomass-based products are the cultivation and transport of the biomass and, in the PBtL paths, also the electricity for electrolysis. In the case of biomethane, the plant-internal provision of heat and electricity via NOx emissions from the biogas CHP makes the greatest contribution to the summer smog potential. This contribution is more pronounced in the biomethane paths with amine scrubbing due to the higher energy demand.

In 2050, results will improve for almost all products and cases of operation. This is mainly due to lower electricity demand due to higher electrolysis efficiency and decreasing summer smog potential of electricity per kilowatt-hour. The materials used in the construction of the electricity generation, synthesis and separation plants (mainly steel, aluminium and copper) are responsible for lower emissions due to modified production processes and higher recycling rates (Chapter 5.1.2). For the biomass-based products, there is no improvement for most paths, since the main causes – cultivation and transport of the biomass and energy supply in the biogas plant – do not change. In the PBtL paths, the improvement of the electricity for electrolysis has a positive effect.

Averaged over all supply paths, NOx with 69%, NMVOC with 14%, SO_2 with 8% and CO with 5% contribute to the summer smog potential in 2050.

The differences in the results for the operating cases "full-load hours of synthesis plant" and "full-load hours of power source" are proportionally similar in 2050 as in 2015. This is again due to the reduced photochemical ozone creation emissions from the production of the materials used to build the power generation, synthesis and separation plants.

Figure 69: Summer smog potential – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.5 Ozone depletion

Figure 70 shows the ranges of ozone depletion potential for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. The extreme values are also very far apart in this impact category. The production of biomethane from biowaste/green cuttings with CO_2 capture by amine scrubbing path 57 in 2015 leads to a calculated burden of around 8,700% of the average fossil reference. The most favourable path 16 with FT-PBtL synthesis from the residual material straw will lead to a relief of about 60% of the fossil reference in 2050.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of results, with methanol performing slightly worse. Electricity-based methane (SNG) performs slightly better than liquid energy carriers. The hydrogen paths clearly show the best results for ozone depletion potential. The paths using the general electricity mix are among the worst for all products in 2015.

The main source of ozone depletion potential for all electricity-based products is electricity for electrolysis, especially from concentrated solar power (CSP) with liquid salt heat storage. The storage medium consists of nitrate salts, which cause significant N_2O emissions during production, which contribute significantly to ozone depletion. The construction of the electrolysers, synthesis and deposition plants plays a significant role in the ozone depletion potential only for deposition from air (DAC). DAC can even make a contribution of up to 85% – for example in path 48 (FT-PtL, DAC, PV in Germany) in the operating case "full load hours power source". The DAC plant modelled according to the manufacturer's specifications uses an anion exchange resin which releases ozone-depleting tetrachloromethane (R-10) during production.

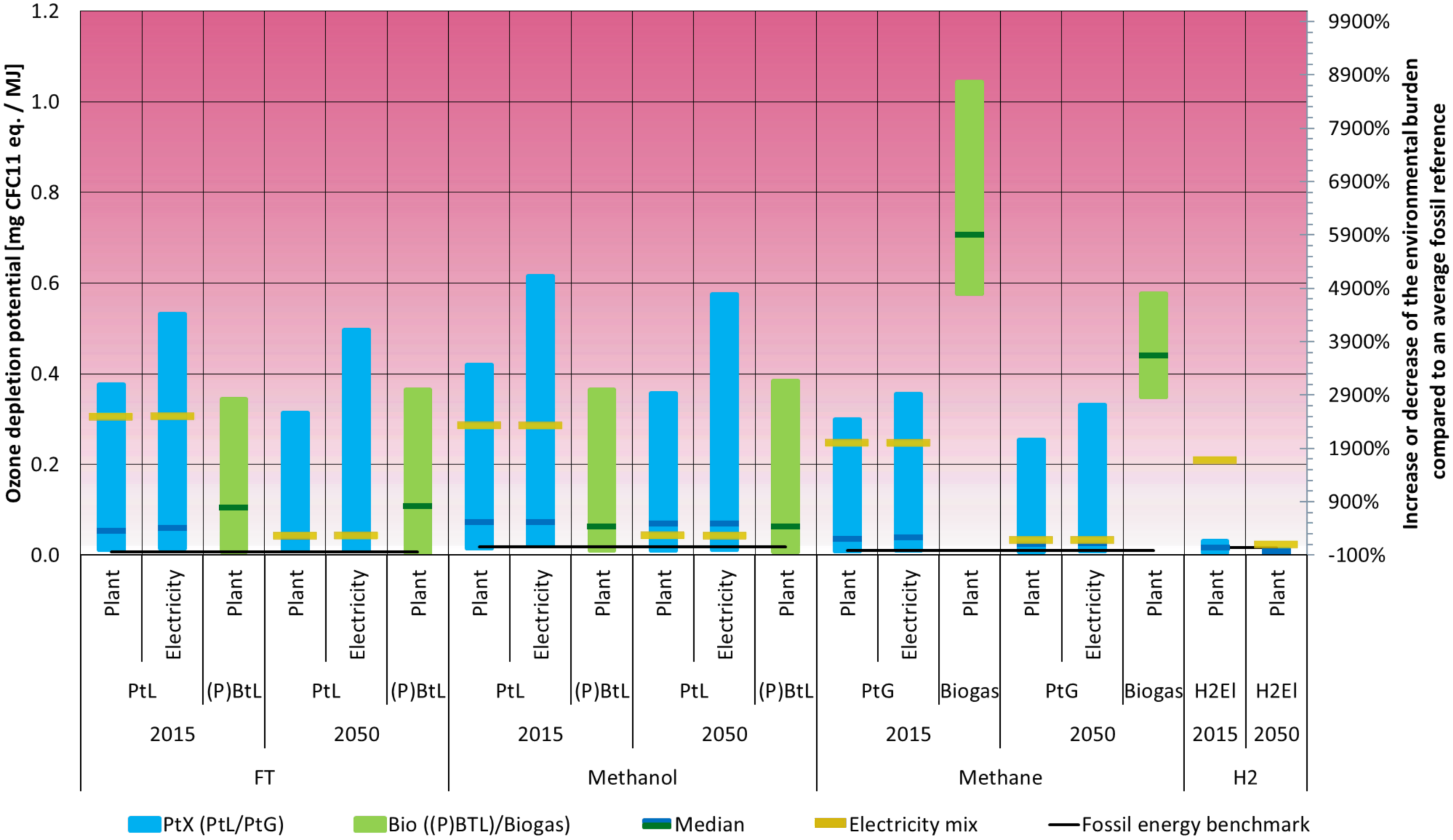
In 2015, the biomass-based liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will perform slightly better in terms of their ozone depletion potential compared to those based purely on electricity. However, biomethane shows significantly worse results than electricity-based methane. The main sources of the ozone depletion potential for all paths with cultivated biomass are N_2O emissions from cultivation. In the case of biogas, fermentation residue storage and output as well as emissions from the biogas CHP contribute to the plant-internal provision of heat and electricity.

In 2050, the results for almost all products and cases of operation improve little. This is mainly due to the only slight decrease in the ozone depletion potential of electricity generation. For the biomass-based products, there is no improvement for most paths, as the main causes – cultivation of the biomass, fermentation residue storage and output, and energy supply in the biogas plant – do not change.

Averaged over all supply paths, N_2O with 82% and carbon tetrachloride with 17% contribute to the specific ozone depletion potential in 2050.

The differences in the results for the operating cases "full load hours synthesis plant" and "full load hours power source" are similar for the years 2015 and 2050 and are due to the significantly higher contribution of CO_2 capture from the air in the operating case "power".

Figure 70: Ozone depletion potential – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.6 Particulate matter

Figure 71 shows the ranges of particulate matter emissions for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. Only a few supply paths perform better than the fossil reference and thus provide relief. The extreme values in this impact category are also very far apart. While the production of methanol with CO_2 capture from the air and electricity from PV in Germany (path 32) in the "full-load hours power source" mode of operation in 2015 leads to a calculated load of around 2,000% of the average fossil reference, the most favourable path (path 1, FT-BtL from straw in Germany) has a relief of around 40% in 2050.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of performance, with methanol performing worse. Electricity-based methane (SNG) performs slightly better than liquid energy carriers. The hydrogen paths clearly show the best results for particulate matter emissions. The paths using the general electricity mix are among the worst for all products in 2015 – especially when compared to those using the "full-load hours synthesis plant" mode of operation.

For all electricity-based products, the main source of the particulate matter potential is the plants generating electricity for electrolysis – especially via the processes and materials described in Chapter 5.3.4.1 However, the construction of the electrolysers, synthesis and separation plants plays a greater role in particulate matter emissions than in global warming potential. In the case of paths with CO_2 removal from the air, all plants together can even contribute up to 60% – especially in the "full-load hours power source" mode of operation.

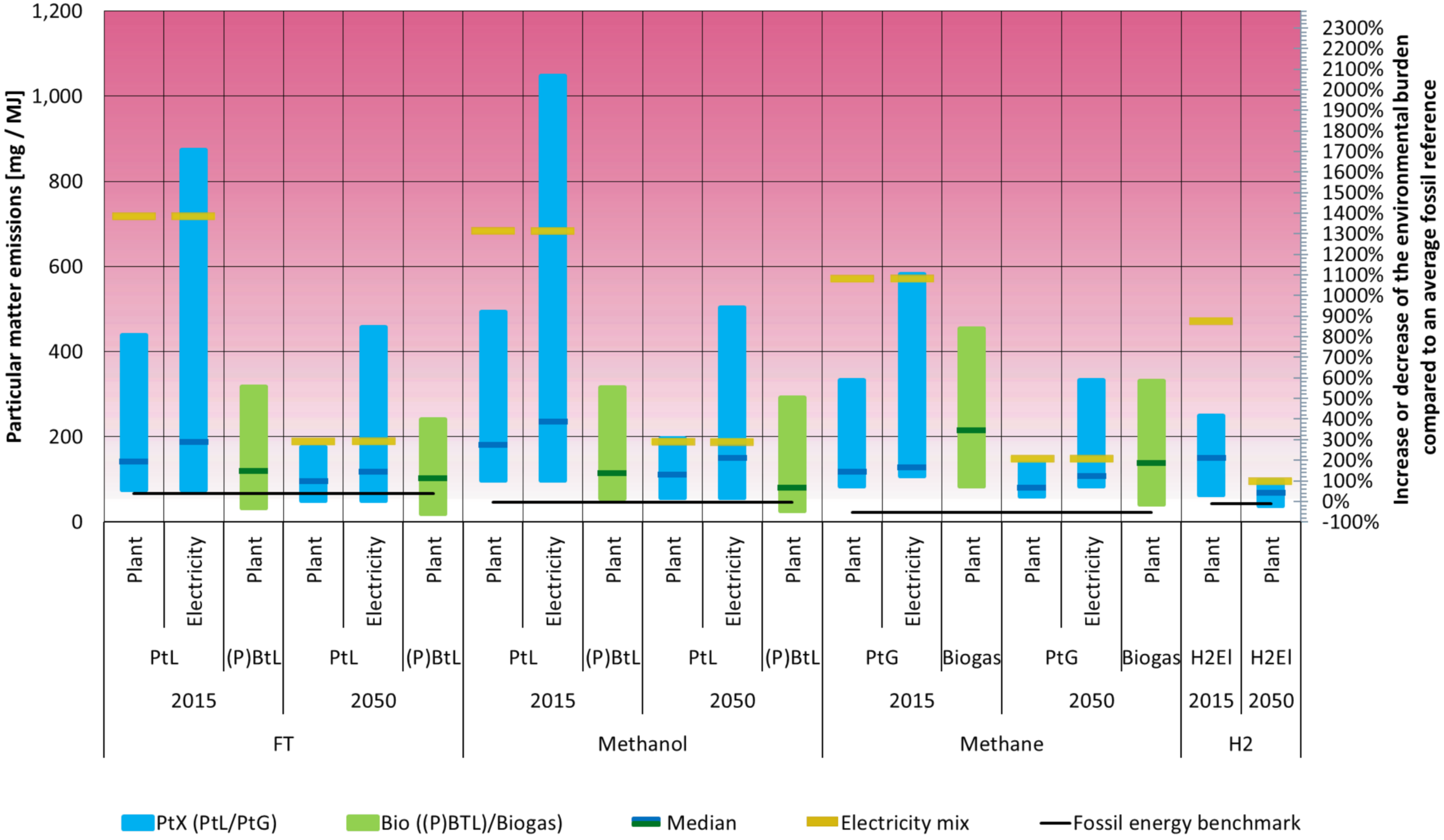
In 2015, the biomass-based liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will perform better in terms of their particulate emissions compared to those based purely on electricity. Biomethane tends to perform slightly worse than electricity-based methane. The main sources of particulate emissions for all biomass-based products are the cultivation and transport of the biomass and, in the PBtL paths, the electricity used. In the case of biomethane, the plant-internal provision of heat and electricity from the biogas CHP makes the largest contribution to particulate matter emissions. In the biomethane paths with amine scrubbing, this contribution is more pronounced due to the higher energy demand.

In 2050, the results for almost all products and cases of operation will improve significantly. This is mainly due to the decreasing particulate emissions from power generation. For the biomass-based products, there is only a slight improvement for most paths, as the main causes – cultivation and transport of the biomass and energy supply in the biogas plant – do not change.

Averaged over all supply paths, NO_x with 36%, SO_2 with 34%, NH_3 with 15% and direct PM_{10} releases with 15% contribute to particulate matter emissions in 2050.

The differences in the results for the operating cases "full-load hours synthesis plant" and "full-load hours power source" are similarly marked for the years 2015 and 2050 and are due to the contribution of the construction of all plants (electrolysers, synthesis plants and separation plants).

Figure 71: Particulate matter emissions – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.7 Cumulative energy demand

Figure 72 shows the ranges of the cumulative energy demand for all products. The results are divided into path groups according to electricity and biomass input. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. The extreme values are also very far apart in this impact category. While the production of methanol and FT fuel with electricity and CO_2 from geothermal energy in Iceland will lead to a calculated additional burden of over 500% of the average fossil reference for the reference year 2015, the most favourable path (path 57, biomethane from biowaste/green cuttings with CO_2 capture by pressurised water scrubbing) shows a relief of around 95%.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges at high levels, while electricity-based methane (SNG) and hydrogen perform significantly better. This is also the case if the very unfavourable paths 15 and 37 (geothermal energy in Iceland) are excluded from the calculation. Then the worst path for FT fuel (path 10, PtL synthesis with PV electricity and DAC in Germany) is still 280% and for methanol (path 32, PtL synthesis with PV electricity and DAC in Germany) 350% of the average fossil reference. The worst path for synthetic natural gas (path 48, PtG synthesis with PV electricity and DAC in Germany) is 220%. Paths using the general electricity mix are among the two worst paths for all products in 2015. For all electricity-based products, the main contributions to the cumulative energy input are the electrolysis electricity generation facilities – mainly via the processes and materials described in Chapter 5.3.4.1– and, to a lesser extent, CO_2 capture from the air. The construction of the electrolysers, synthesis and separation plants play a minor role.

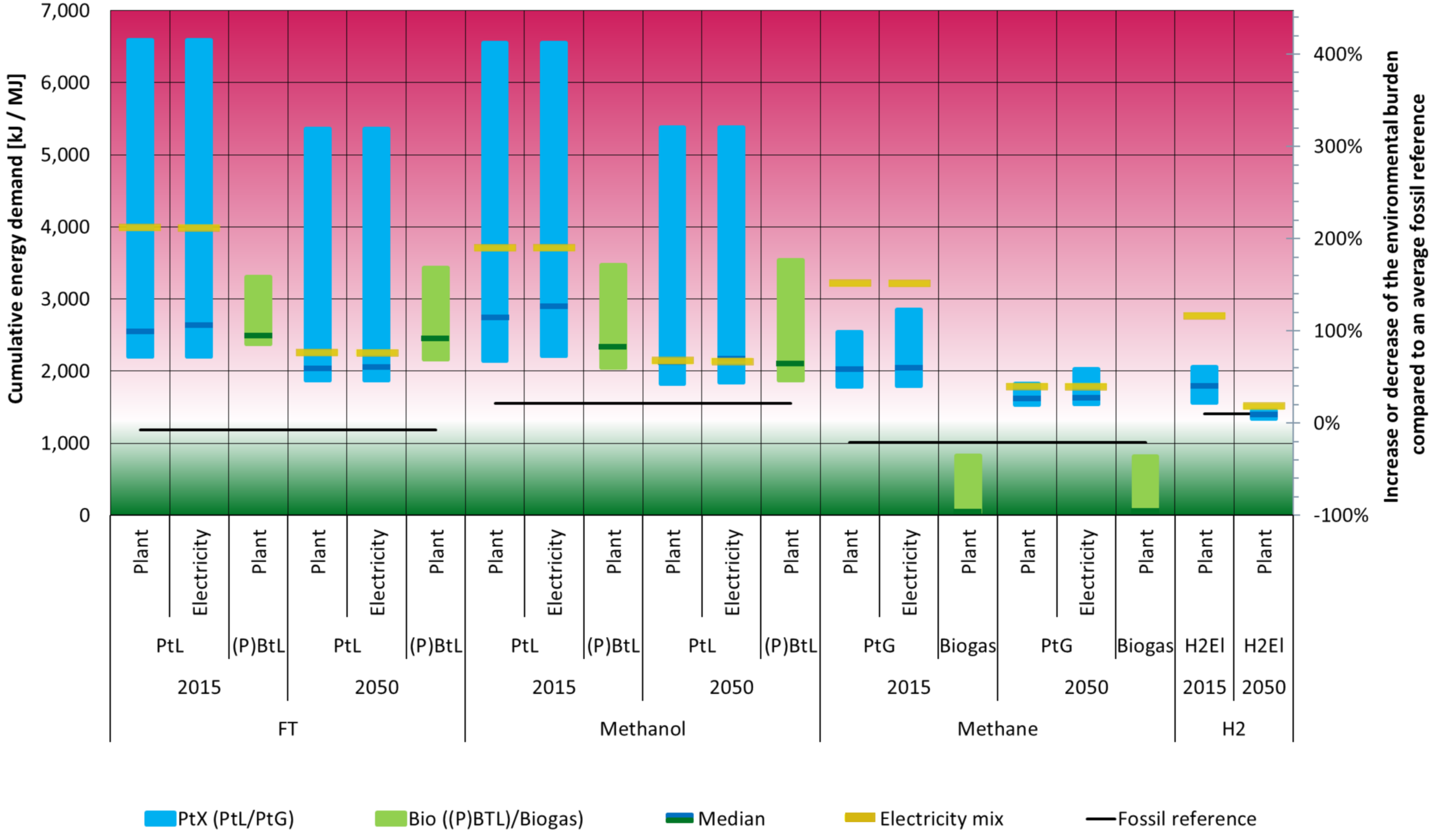
The biomass-based, liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will not do better in 2015 than the fully electricity-based ones, if the exceptionally unfavourable paths 15 and 37 (geothermal energy in Iceland) are excluded from consideration. Biomethane has a clear advantage over SNG and is the only path that performs better than the reference in 2050. For all biomass-based products, the main contributions to the cumulative energy input are the cultivation and transport of the biomass and, in the PBtL paths, the electricity for electrolysis.

In 2050, the results will improve for almost all products and cases of operation. This is mainly due to the improved efficiency of electrolysis and CO_2 removal from the air. There is no improvement for the purely biomass-based products, as the main causes – cultivation of the biomass and energy supply in the biogas plant – do not change.

Averaged over all supply paths, solar energy contributes 36%, wind energy 30% and biomass 18% to the cumulative energy demand in 2050, geothermal energy 9%, hydropower 4% and fossil fuels (outside the EU) 3%.

The results for the operating cases "full-load hours synthesis plant" and "full-load hours power source" differ only slightly in terms of cumulative energy consumption, as the contribution of the plants is relatively small.

Figure 72: Cumulative energy use – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.8 Land Use

Figure 73 shows the ranges of space requirements for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. The extreme values are also very far apart in this impact category. While the production of methanol with CO_2 capture from the air and electricity from PV in Germany (path 32) in the "full-load hours power source" mode of operation will lead to a calculated impact of around 60,000% of the average fossil reference in 2015, the most favourable path (path 1, Fischer-Tropsch, BtL, residual straw) will only have an impact of around 130% in 2050.

In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of results, with methanol performing slightly worse. This is because less heat can be extracted from methanol synthesis and used in CO_2 capture. The paths for electricity-based methane (SNG) and hydrogen perform better than those for liquid energy carriers. The paths using the general electricity mix are among the ones with the least space requirements in 2015 and 2050 for all products.

For all electricity-based products, the main contribution to the space requirement is the electricity for electrolysis and for the energy-intensive CO_2 capture from the air. The construction of the plants is only of minor importance.

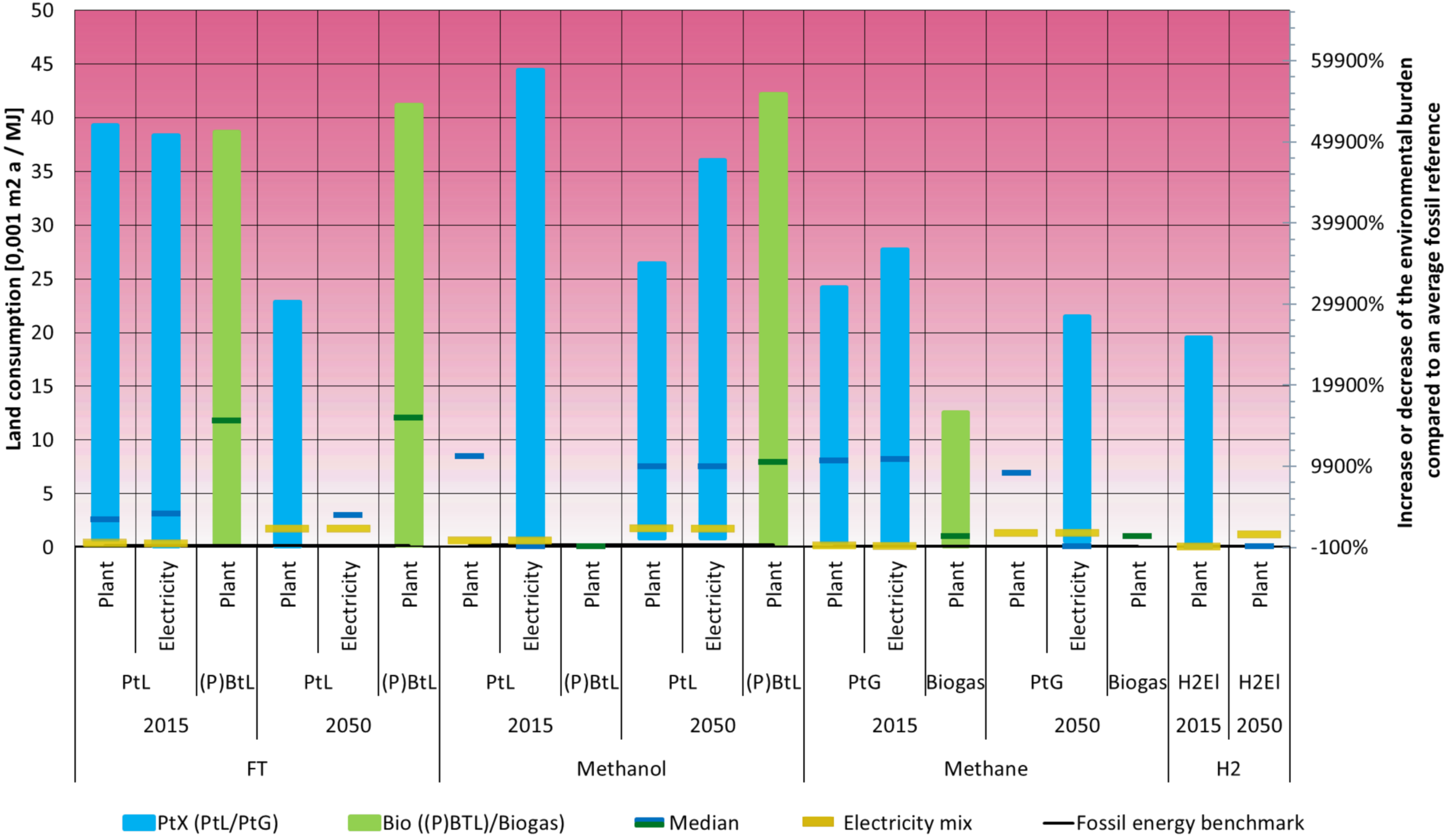
The biomass-based, liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will perform just as poorly in 2015 in terms of their land requirements compared with those based purely on electricity. Biomethane has a clear advantage over electricity-based methane (SNG). The hydrogen paths provide ranges comparable to those of SNG. The main contributions to land requirements for all biomass-based products are the cultivation of biomass and, in the PBtL paths, the electricity used.

In 2050, the results for fully electricity-based products will improve somewhat. This is mainly due to the increasing efficiency of electricity generation and CO_2 capture from the air. The electricity mix in 2050 will require more space than in 2015.

For the biomass-based products, the range remains unchanged.

The differences in the results for the operating cases "full-load hours synthesis plant" and "full-load hours power source" are similarly marked for the years 2015 and 2050 and are due to the contribution of all plants (electrolysers, synthesis plants and separation plants).

Figure 73: Land use – Ranges 2015 and 2050 and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.9 Water consumption

Figure 74 shows the ranges of water consumption for all products. The results are divided into path groups according to electricity and biomass use. The ranges are shown separately for the reference years 2015 and 2050 and the two cases of operation considered.

In the overall picture, almost all products and paths – and thus also the medians of the path groups – lie above the fossil reference. The extreme values are also very far apart in this impact category. The production of FT fuel with wood from short-rotation plantations leads to a calculated impact of around 14,000,000% of the average fossil reference. The most favourable path (path 60, biomethane from biowaste/green cuttings with CO_2 capture by membrane separation) shows a relief of around 55% in 2050.

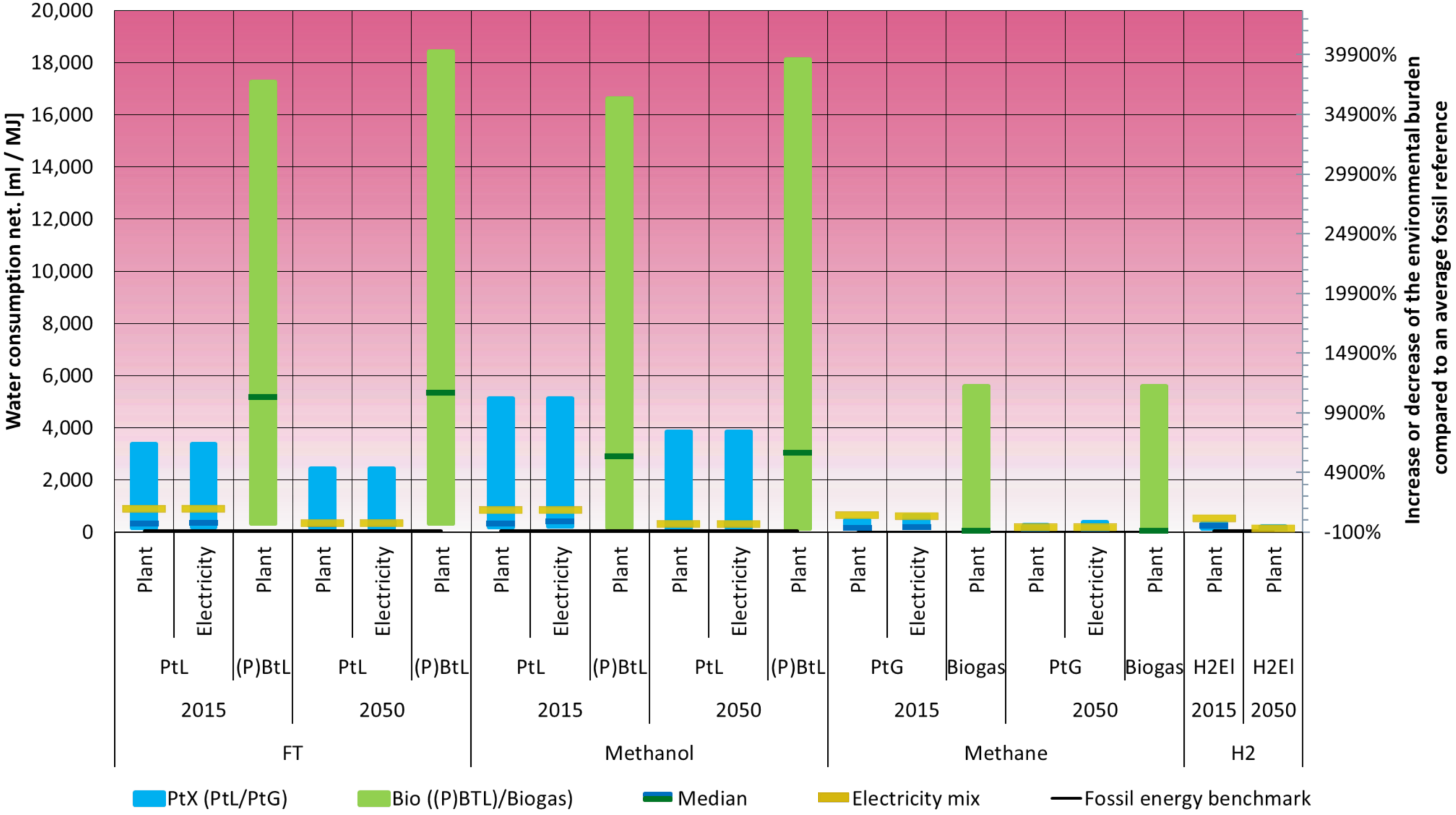
In 2015, the **fully electricity-based** PtL energy carriers (FT fuels and methanol) will be dominated by paths 15 and 37 (geothermal energy in Iceland), which are far ahead of the second worst paths 10 and 32 (FT and methanol PtL with PV electricity and DAC in Germany). The paths with the use of the general electricity mix are among those with lower water consumption in 2015 and 2050 for all products. The hydrogen paths provide very favourable ranges comparable to the SNG. For all electricity-based products, the main contribution to water consumption is made by the electrolysis power generation facilities – especially via the processes and materials described in Chapter 5.3.4.1. The construction of the synthesis and separation plants is only of minor importance.

In 2015, the biomass-based liquid energy carriers (FT fuel and methanol from (P)BtL syntheses) will perform much worse in terms of water consumption than the fully electricity-based ones. Biomethane is also at a clear disadvantage compared to electricity-based methane (SNG). The main contributors to water consumption for all biomass-based products are the cultivation of biomass.

In 2050, the results for fully electricity-based products will improve somewhat. This is mainly due to the increasing efficiency of electricity generation and CO_2 capture from the air. The electricity mix in 2050 has a lower water consumption than in 2015, while the range remains unchanged for the biomass-based products.

The differences in the results for the operating cases "full load hours synthesis plant" and "full load hours power source" are similar for the years 2015 and 2050 and are due to the contribution of all plants (electrolysers, synthesis plants and separation plants). In the diagram, the differences are hidden by the paths with electricity from geothermal energy.

Figure 74: Water consumption (net) – 2015 and 2050 ranges and potential increase or decrease of impact compared to a fossil reference



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5.3.4.3.10 Cumulative raw material demand

Figure 76 shows the ranges of the cumulative raw material demand for all products. The results are divided into path groups according to electricity and biomass input. The ranges are shown separately for the reference years 2015 and 2050 and for the two cases of operation considered.

In the overall picture, all path groups show both additional burdens and relief compared to the average fossil reference. The production of methanol with CO_2 capture from the air and electricity from PV in Germany (path 32) will lead to a calculated burden of around 1,300% of the fossil reference in 2015. The most favourable path 1 with FT-BtL synthesis from the residual straw material shows a relief of around 90% in 2050.

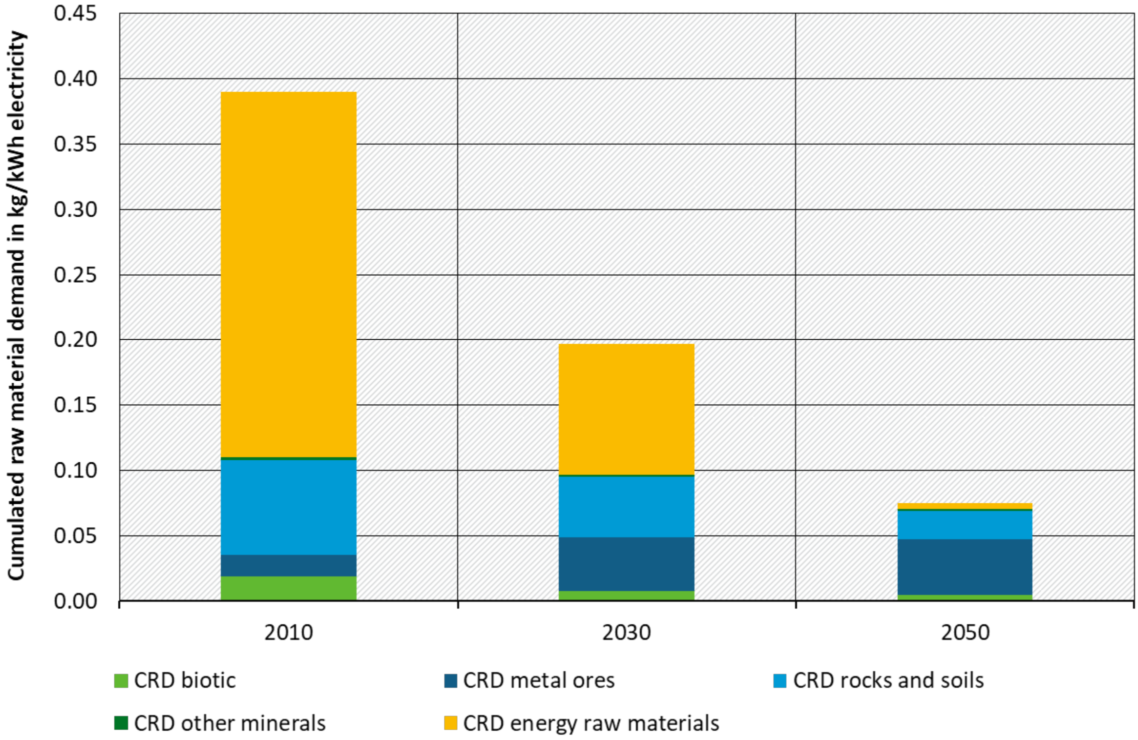
In 2015, **fully electricity-based** PtL energy carriers (FT fuels and methanol) show similar ranges of performance, with methanol performing worse. This is because the synthesis plant makes a larger contribution and less heat can be extracted from the methanol synthesis and used in CO_2 capture. The best paths for electricity-based methane (SNG) perform slightly worse than liquid energy carriers. There, paths 15 and 37 (both with geothermal energy in Iceland) have the lowest raw material requirements. The hydrogen paths have a narrow range and not a bad path. The paths using the general electricity mix are among the worst for all products in 2015 – in the "full-load hours synthesis plant" mode of operation even by a considerable margin.

For all electricity-based products, the main contribution to the cumulative raw material demand is made by the electrolysis power generation plants – mainly via the processes and materials described in Chapter 5.3.4.1. However, the construction of the electrolysers, synthesis and separation plants plays a greater role in the cumulative raw material input than in the global warming potential. In the case of paths with CO_2 capture from the air, all plants together can even contribute up to almost 70% – especially in the "full-load hours power source" mode of operation. The construction of the lines for high-voltage direct current transmission (HVDC) in paths 5, 27, 45 and 50 also contributes up to 30% of the raw material costs.

The biomass-based, liquid energy carriers (FT fuel and methanol from (P)BtL syntheses), with their cumulative raw material input, will perform better in 2015 than the fully electricity-based ones. Biomethane also has a clear advantage over electricity-based methane (SNG). For all biomass-based products, the main contributions to the cumulative raw material demand are the cultivation and transport of the biomass, the plants and, in the PBtL paths, the electricity used.

In 2050, the results for almost all products and cases of operation will improve significantly. This is mainly due to the decreasing raw material costs of electricity generation. Figure 75 shows the cumulative raw material demand of the German electricity mix in 2010, 2030 and 2050. It can be seen that, although the shares of energy raw materials, stone, earth and biomass are declining sharply, there is still a need for more raw materials. However, the cost of metallic raw materials is increasing proportionately and significantly in absolute terms.

Figure 75: **Cumulative raw material demand of the German electricity mix in 2010, 2030 and 2050**



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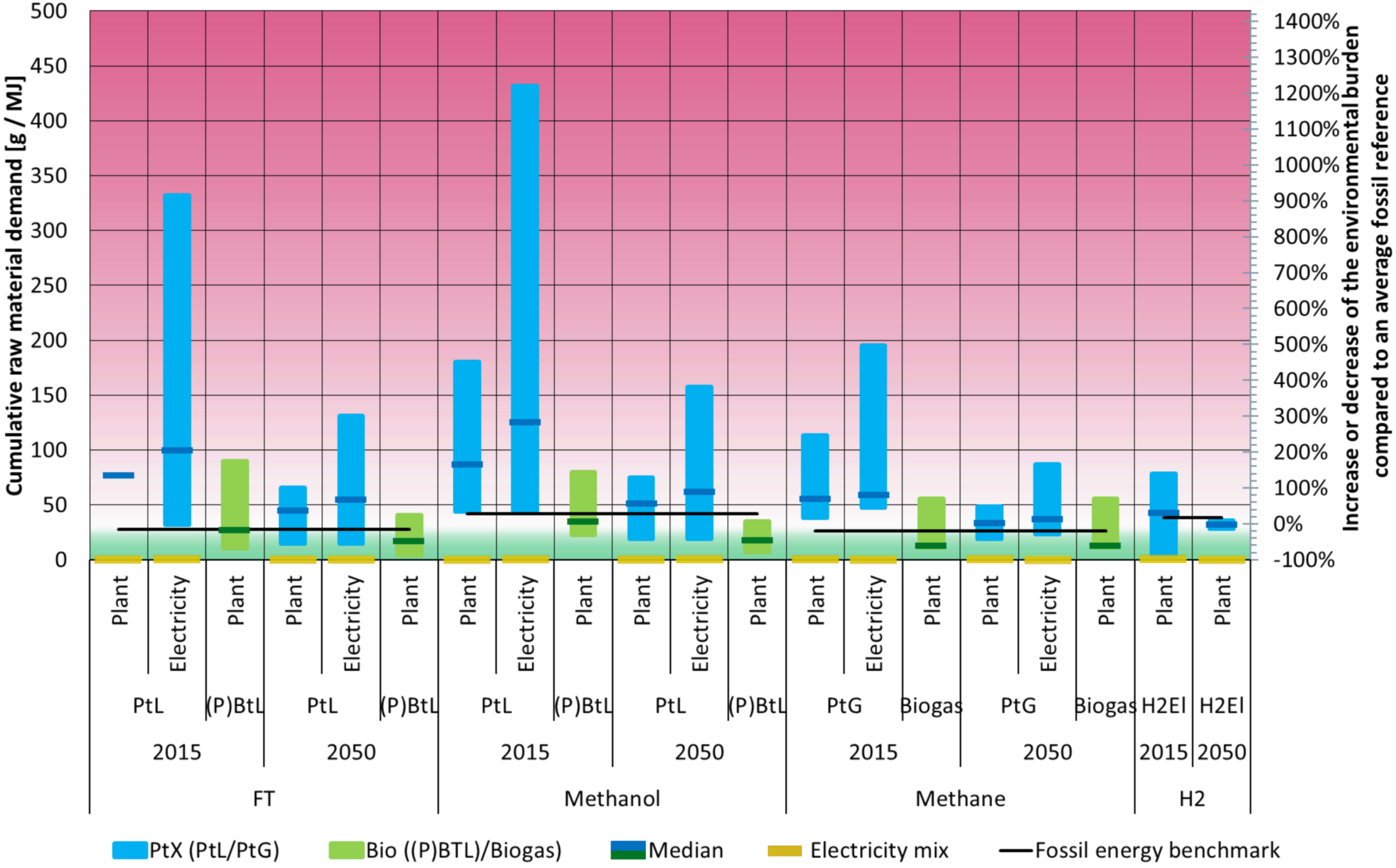
For the biomass-based products, there are only slight improvements for most paths, as the main causes – cultivation and transport of the biomass – do not change.

Averaged across all supply paths, metals (53%), minerals (32%), mineral raw materials (7%) and energy raw materials (7%) contribute to the specific cumulative raw material demand in 2050.

The differences in the results for the operating cases "full-load hours synthesis plant" and "full-load hours power source" are similarly marked for the years 2015 and 2050 and are due to the contribution of all plants (electrolysers, synthesis plants and separation plants).

Figure 76: Cumulative raw material demand – ranges 2015 and 2050 and potential increase or decrease of impact compared to a fossil reference



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5.3.5 Conclusions life cycle assessments

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 5.1.2[13].

  - 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.

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[13] It is assumed, as in the RESCUE study, that the world outside Europe is also undergoing a transformation towards greenhouse gas neutrality but with a delay of 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, which are discussed in Chapter 4.2. 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 5.3.4.2).

- 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.

5.3.5.1 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 5.1.2) 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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6 Cost estimates

The cost estimates are based on a comparison of the 62 supply paths in terms of their current (2015) and projected long-term (2050) costs. The provision costs of storable renewable energy carriers for the different supply paths are estimated and the main constraints on these costs are identified. The significant differences between the individual storable renewable energy carriers and their main causes are presented.

6.1 Methodology and cost data used

6.1.1 Methodology

In an overall cost comparison, the current specific provision costs of the final energy carriers studied are determined, always estimating the costs of the entire supply path. The following cost categories are considered:

- Capital cost of the investment for the construction of the production facilities (annuity of the investment)
- Variable production costs:
  - Costs of the energy carriers used
  - Energy costs (process heat, electricity)
  - Costs for operating materials
  - Transport costs
- Fixed productions costs:
  - Personnel costs
  - Maintenance and servicing costs
- Revenue for by-products

The consideration of the revenues for by-products incurred during the production of the final energy carriers is alligned with the approach in the life cycle assessment.

The annual production costs [€/a] or the specific production costs [€/MWh, €/MJ] are calculated. All costs are without taxes.

The annual production costs are calculated:

Annuity [€/a] + variable production costs [€/a] + operational and other fixed costs [€/a] - revenue for by-products [€/a].

1. Annuity [€/a]

Annuity is the annually constant amount from the investment costs assuming an imputed interest rate and the useful life of plant components according to the following formula

$$a = C_0 \cdot ANF_{n,i}$$

$$ANF_{n,i} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1}$$

a Annuity [€/a]

C_0 Investment costs [€].

$ANF_{n,i}$ Annuity factor for the useful life n and the interest rate i

I Imputed interest rate [%].

n Useful life [a]

For the imputed interest rate and the useful life of the plant components, values from technical literature (such as regulations, e.g., DIN EN 15459, technical articles, reports) are used.

2. Variable production costs [€/a].

The variable production-related costs include the costs caused by the level of energy production, mainly costs of the energy carriers used, energy costs (process heat, electricity), costs of operating materials, transport costs.

3. Fixed production costs [€/a].

They include maintenance, repair, and personnel costs.

For the calculation of the specific production costs [€/MWh], the annual production costs are related to the amount of energy in the carriers produced: annual production costs [€/a] / amount of energy in the carriers produced [MWh/a].

This cost analysis only examines the technology-related costs described above for plant construction and operation for the production of storable renewable energy carriers and thus represents the relationship between technology parameters or future technology performance potentials and technology-related cost parameters. Other cost variables of economic analyses (e.g., taxes, subsidies) and economic cost-benefit aspects, in particular external environmental costs, are not considered in this study. For a comparative assessment of the environmental costs of renewable and fossil energy systems, the energy service provided by the energy carriers must also be taken into account, but this was not the subject of this study.

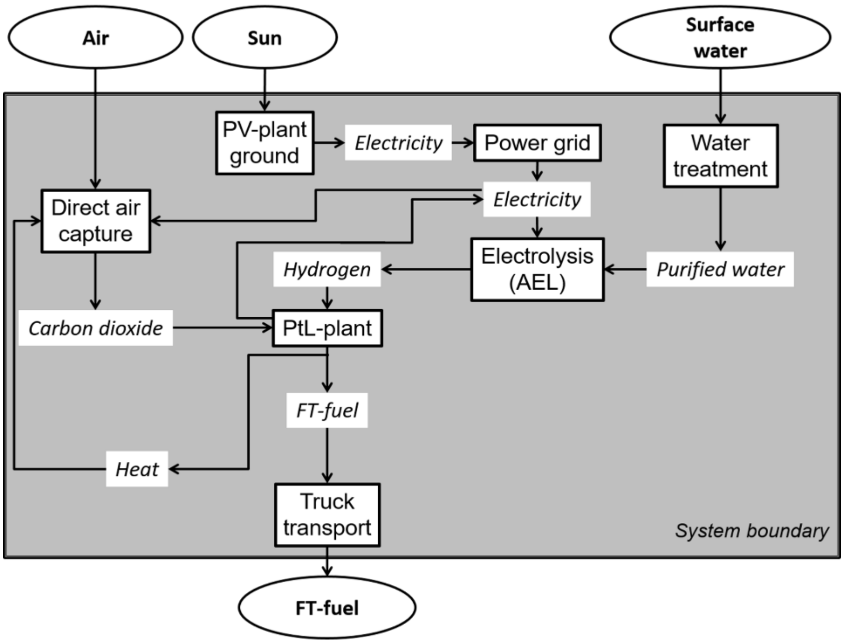
The systematics of cost estimation is based on the same assumptions as the LCA (see Chapter 5.1). These are layed out again below in their application to cost estimates, using the exemplary system diagram of the supply path "10_FT/PVfrei/AEL/DAC/LKW_D" shown in Figure 77.

For a supply path, a system diagram describes the system boundary for all cost-relevant processes, intermediates and co-products within the system boundary with the free input from the environment at the top and with the products at the bottom of the system boundary. System diagrams were created for all 62 supply paths and are part of the data sheets in Appendix A.

Intermediate products, which serve as output of one process and as input to another process, are accounted for and thus have an impact on costs. In Figure 77 for example, the PtL plant generates the by-product electricity by using part of the waste heat in a steam turbine, which is used to operate the electrolysis. This amount of electricity reduces the amount of PV electricity needed to generate the necessary amount of hydrogen in the electrolysis and thus leads to lower hydrogen costs. The PtL plant also supplies heat that is used in the process of CO_2 capture. This systematic approach to cost estimation allows the presentation of specific cost advantages by integrating the various processes in the different supply paths. Possible by-products (e.g., fertiliser in supply paths with biomass) are taken into account in the cost estimate with revenues at market prices.

Among the most significant cost-determining factors are the annual full-load hours of the various technologies within a supply path. In particular the annual hours of renewable electricity generation from sun or wind differ significantly from the maximum operating hours of the synthesis plants. Chapter 5.1.3.2 explains two variants of how this aspect was dealt with in the LCA. Accordingly, two sensitivity calculations were also carried out in the cost estimate for selected supply paths in addition to main case 1 (electrolyser with power supply from the power source assigned to the path, CO_2 capture, and the synthesis plant operate with the maximum possible annual operating hours run around 8000 h/a): In one case (main case 2), electrolyser, CO_2 capture, and synthesis plant operate only the number of hours corresponding to the full load hours of the assigned power source. In another case (main case 3), which was only considered in the cost analysis, the electrolysers, CO_2 capture, and the synthesis plants also run the maximum possible annual operating hours, but the electricity from the assigned power source is only supplied according to the operating hours of the power generation plant, the rest of the electricity comes from the grid (at the industry electricity price).

Figure 77: Exemplary system diagram for supply path 10



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6.1.2 Cost data used

The basic technical and economic data for cost estimation of the technologies investigated were presented in Chapter 2 and Chapter 4 and are also used here.

In the following overview, the data sources used for individual technologies and processes of the supply paths are compiled and arranged according to cost categories. Further data sources on factors influencing specific production costs are listed in chapter 6.2.

- Capital costs

Table 31: Data sources Investment costs for electricity generation, synthesis plants

Power generation	Data source	Synthesis plants	Data source
PV ground-mounted	Schickk 2018	Fischer-Tropsch-BTL, -PBtL	Albrecht 2016
Wind onshore	Schick 2018	Fischer-Tropsch-PtL (MEA), -PtL (DAC)	Albrecht 2016
Wind offshore	Schick 2018	Methanol-BtL, -PBtL	Albrecht 2016

Power generation	**Data source**	**Synthesis plants**	**Data source**
Water Running Power	Nitsch 2012	Methanol-PtL (DAC)	Albrecht 2016
Geothermal energy	Agora 2018	Power to Gas	Agora 2018
CSP (3.0, PT)	DLR (own calculations)		

Table 32: Data sources Investment costs for hydrogen production, CO_2 capture

Hydrogen production	**Data source**	**CO_2 capture**	**Data source**
Alkaline electrolysis	Schmidt 2017	Biogas upgrading	Billig 2016
PEM Electrolysis	Schmidt 2017	Direct Air Capture (DAC)	Viehbahn 2018
High Temperature Electrolysis	Schmidt 2017	Flue gas MEA scrubbing	Albrecht 2016

- ► Variable costs and revenues linked to consumption

Table 33: Data sources variable costs energy carriers, transport costs

Energy carriers	**Data source**	**Transport costs**	**Data source**
Biomass (straw)	Statistics Austria 2018	Power grid	BDEW 2019
Wood from SRC (Sweden)	UNECE 2018	HVDC	Samweber 2015
Wood from SRC (Germany)	C.A.R.M.E.N. 2018	Gas pipeline	Bucy 2016
Maize	FAO 2018	Ship	Argus 2019
Liquid manure	DLG 2017	Ship LNG	Punnonia 2013
Organic waste, green waste	Own estimate	Truck Europe	Della 2019
Fermentation residues (by-product fertiliser)	Own estimate, FAO 2018		

Table 34: Data sources variable costs Operating materials

Operating materials	Data source	Operating materials	Data source
Oxygen (gasification)	BLS 2019	Process water (desalinated)	Billig 2016
Selexol, MEA (CO_2 scrubber)	BLS 2019	Water treatment (reverse osmosis)	Mena-Water 2019
Nickel, Cobalt, Cr_2O_3 (catalyst)	BLS 2019	KOH (alkaline electrolysis)	BLS 2019

- Fixed production costs

Fixed production costs for personnel, maintenance, and repair and other operating expenses (e.g., insurance) as well as other fixed costs for construction (planning, piping, electrics) were estimated using standard add-on factors related to the investment costs (3% to 5% depending on the technology) [Peters 2017].

The results of the cost estimate take into account the uncertainties of the cost data used and are presented in ranges. The ranges used refer to corresponding figures in the data sources used. For cost data without information on uncertainties, a general 10% range was assumed.

The costs for 2050 were estimated as for 2015 for the same cost categories and on the basis of the same data sources evaluated in Chapters 2 and 4. For individual cost categories (e.g., costs for operating materials), if no literature data were available, separate assumptions were made for cost development. Learning rates for estimating future developments in the investment costs of technologies were implicitly applied in the sources of the cost data used on the basis of the respective required technology expert knowledge; for cost estimation, the results from the literature sources were adopted.

In addition to the results presented in chapter 6.2 the main assumptions and results of the cost estimates are summarised in the data sheets for the 62 supply paths (Annex A).

6.2 Results

In analogy to the LCA, the presentation of the results of the cost estimate shows the influence of the most important factors on the costs of supply paths, such as the choice of power source, conversion technology or location. In addition, the cheapest or most expensive supply paths from a cost perspective within product groups are described. A sensitivity analysis examines the impact of the full-load hours of the power source on the estimated costs.

First, the costs of electricity, hydrogen and CO_2 supply are presented as the main influencing factors for the majority of the 62 supply paths (with the exception of the BtL and biomethane paths) (Chapter 6.2.1). Based on this, the costs are presented at the level of the supply paths for Fischer-Tropsch fuel (Chapter 6.2.2.1), methanol (Chapter 6.2.2.2), synthetic natural gas (Chapter 6.2.2.3), biomethane (Chapter 6.2.2.4) and hydrogen (Chapter 6.2.2.5). The costs are considered for the reference years 2015 and 2050. Individual results are highlighted if they provide special insights into a specific supply path, technologies, raw materials and fuels used or into transport routes.

6.2.1 Costs of electricity, hydrogen and CO_2 supply

6.2.1.1 Power supply

In the 62 supply paths studied, electricity is supplied via 13 technology and site combinations. for which the electricity generation and transmission costs (excluding taxes and levies) have been estimated. The main factors influencing the specific costs of electricity supply [€/MWh] are the investment costs of the generating plants, the lifetime of the generating plants, the site-dependent full-load hours and the costs of electricity transmission with AC or DC (HVDC). The investment costs of the electicity generating plants are the same for the same technology at all sites (for data sources see chapter 6.1.2). The expected development of investment costs until 2050 is shown in Table 35. The site-dependent full-load hours were modelled in Chapter 4 and are compiled in Table 36. The same full-load hours were assumed for 2015 and 2050. The expected lifetimes of the generation plants and their development until 2050 is shown in the Table 37.

Table 35: Investment costs for renewable electricity generation [M€/MW]

Technology	2015	2050	Reduction until 2050
Wind onshore (strong wind)	1.4	1.2	14%
Wind offshore	3.8	2.9	24%
Photovoltaic ground-mounted (PV)	1.2	0.6	50%
Concentrating Solar Power (3.0 PT)	5.6	2.6	54%
Geothermal energy	2.5	2.2	12%
Hydropower	5.0	5.0	0%

Table 36: Mean annual full load hours of renewable electricity generation [h/a]

Technology	Location	2015	2050
Wind onshore (strong wind)	Germany	2,963	2,963
	Morocco	2,946	2,946
Wind offshore	Germany	4,234	4,234
Photovoltaic ground-mounted (PV)	Germany	958	958
	Morocco	1,729	1,729
	Saudi Arabia	1,777	1,777
Concentrating Solar Power (3.0 PT)	Morocco	6,189	6,189
	Saudi Arabia	6,537	6,537
Geothermal energy	Iceland	7,620	7,620
Hydropower	Scandinavia	5,000	5,000

Table 37: Lifetime of renewable electricity generation plants [a].

Technology	2015	2050
Wind onshore (strong wind)	20	20
Wind offshore	20	25
Photovoltaic ground-mounted (PV)	20	30
Concentrating Solar Power (3.0 PT)	25	25

Technology	2015	2050
Geothermal energy	30	30
Hydropower	40	40

The following two paragraphs describe the calculation of electricity transmission costs. For AC grids, the network charge in the industry electricity price in 2015 in Germany is on average 24 €/MWh (Bundesnetzagentur 2018). The network charge for 2050 has been estimated at 41 €/MWh on the basis of a two percent cost increase per year. Increasing demands on the future operation of electricity grids due to changes in the generation mix and the liberalisation of the energy market will lead to an expected increase in the technical costs of transmission. The transmission costs in AC grids described above were also used for the generation locations Iceland, Sweden, Morocco and Saudi Arabia for simplification.

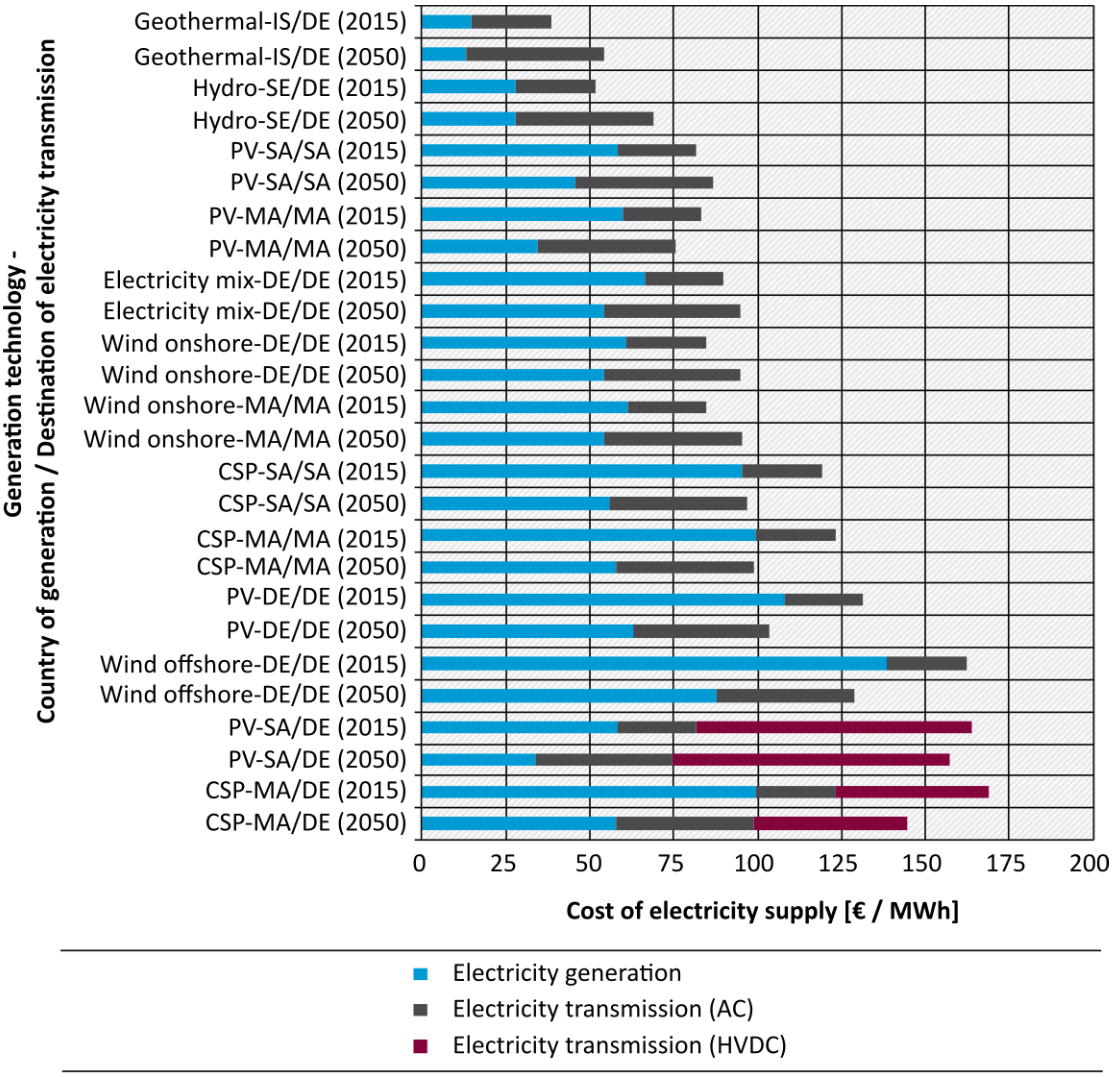
The costs of transmitting electricity generated in Morocco and Saudi Arabia to Germany via direct current (HVDC) transmission were estimated for four supply paths (5, 27, 45, 50). The investment costs for HVDC transmission differ considerably depending on whether the transmission is carried out as an overhead line (0.7-1.4 M€/MW) or as an underground cable (1.2-16 M€/MW) (Samweber 2015). The wide cost range for underground cables is less due to the technology itself rather than to the installation of the cables. The cost of laying underground cables varies depending on the location (e.g., densely populated area, forest or nature reserve, existing cable route). For the cost estimate, the costs for HVDC transmission were calculated on the assumption that 85% of the route from Saudi Arabia or Morocco to Germany is laid as overhead line and 15% as cable. With the mean values of the above-mentioned range of investment costs and full utilisation of the lines, the result is 46 €/MWh for electricity transport from Morocco and 82 €/MWh from Saudi Arabia. The costs for HVDC transmission (lifetime 50 years) will not change over the period until 2050.

The cost estimate for electricity from the German electricity mix three supply paths (22, 42, 54) was based on the industry electricity price, which in 2015 was 90 €/MWh for procurement, grid charges and sales (excluding levies and taxes) (BDEW 2019). The costs in 2050 (95 €/MWh) were assumed to be the cheapest renewable electricity source in Germany based on the calculated generation costs for electricity from wind onshore plants.

The results of the specific electricity supply costs with the cost shares for generation and transmission for all 13 technology/site combinations are shown in Figure 78 for the years 2015 and 2050. Electricity from geothermal energy in Iceland and hydropower in Sweden have the lowest costs in 2015 and 2050 respectively, although the supply costs in 2050 are estimated to be higher than in 2015 due to rising grid costs for transmission to Germany. The cheapest technology for electricity generation in Germany is onshore wind power. The costs are in a similar range to the industry electricity price in Germany. PV electricity generated and utilised in Saudi Arabia or Morocco (in an electrolysis plant) has comparable supply costs. The costs in 2050 are also estimated to be higher than in 2015 due to rising transmission costs. Rising transmission costs until 2050 thus compensate for falling generation costs.

The highest supply costs of electricity generated in Germany are incurred by PV systems and offshore wind turbines. Only electricity generated in Morocco with CSP or in Saudi Arabia with PV and imported to Germany via DC networks has even higher supply costs. These electricity generation technologies still have considerable potential for reducing generation costs, so that in 2050 the supply costs including transmission will be lower than in 2015.

Figure 78: **Specific costs of renewable electricity generation and transmission**



Source: Own representaation, JOANNEUM RESEARCH

6.2.1.2 Hydrogen production

Electrolytic hydrogen production is part of 54 of the 62 supply paths studied. Three different electrolysis technologies are used: alkaline electrolysis (AEL), PEM and high temperature electrolysis (HTEL). The main factors influencing the specific costs of hydrogen production [€/t] are the investment costs of the electrolysis plants, the lifetime, the full load hours and the cost of the electricity used. The investment costs and their development for the reference years 2015 and 2050 are shown in Table 38 (for data sources see Chapter 6.1.2), the useful lifetimes and their expected development until 2050 are shown in Table 39.

The full load hours are the same for the three electrolysis technologies at 8.000 hours per year. The electrolysis is supplied arithmetically from the assigned power source, while power storage units for balancing the different full load hours of the power source and the electrolysis were neglected. The electricity costs for hydrogen production in electrolysis differ due to the influencing factors described in Chapter 6.2.1and, to a small extent, due to the amount of electricity generated within the system boundary of the supply path in the synthesis plant, which is used free of charge (0-2.5% of the electricity required for electrolysis, depending on the supply path). The heat demand of the high temperature electrolysis is covered by waste heat from the synthesis plant.

Table 38: Investment costs for electrolysis plants [€/kWel]

Technology	2015	2050	Reduction until 2050
Alkaline electrolysis AEL	1050	500	52%
PEM Electrolysis	1475	775	47%
High Temperature Electrolysis HTEL	4000	1350	66%

Table 39: Useful lifetime of the electrolysis plants [h].

Technology	2015	2050
Alkaline electrolysis AEL	75,000	90,000
PEM electrolysis	50,000	80,000
High temperature electrolysis HTEL	10,000	90,000

All electrolysis technologies require treated water as operating material. The alkaline electrolysis additionally requires potassium hydroxide. For potassium hydroxide no change in the market price was assumed for 2050, for water rising costs due to an expected increasing scarcity (Table 40).

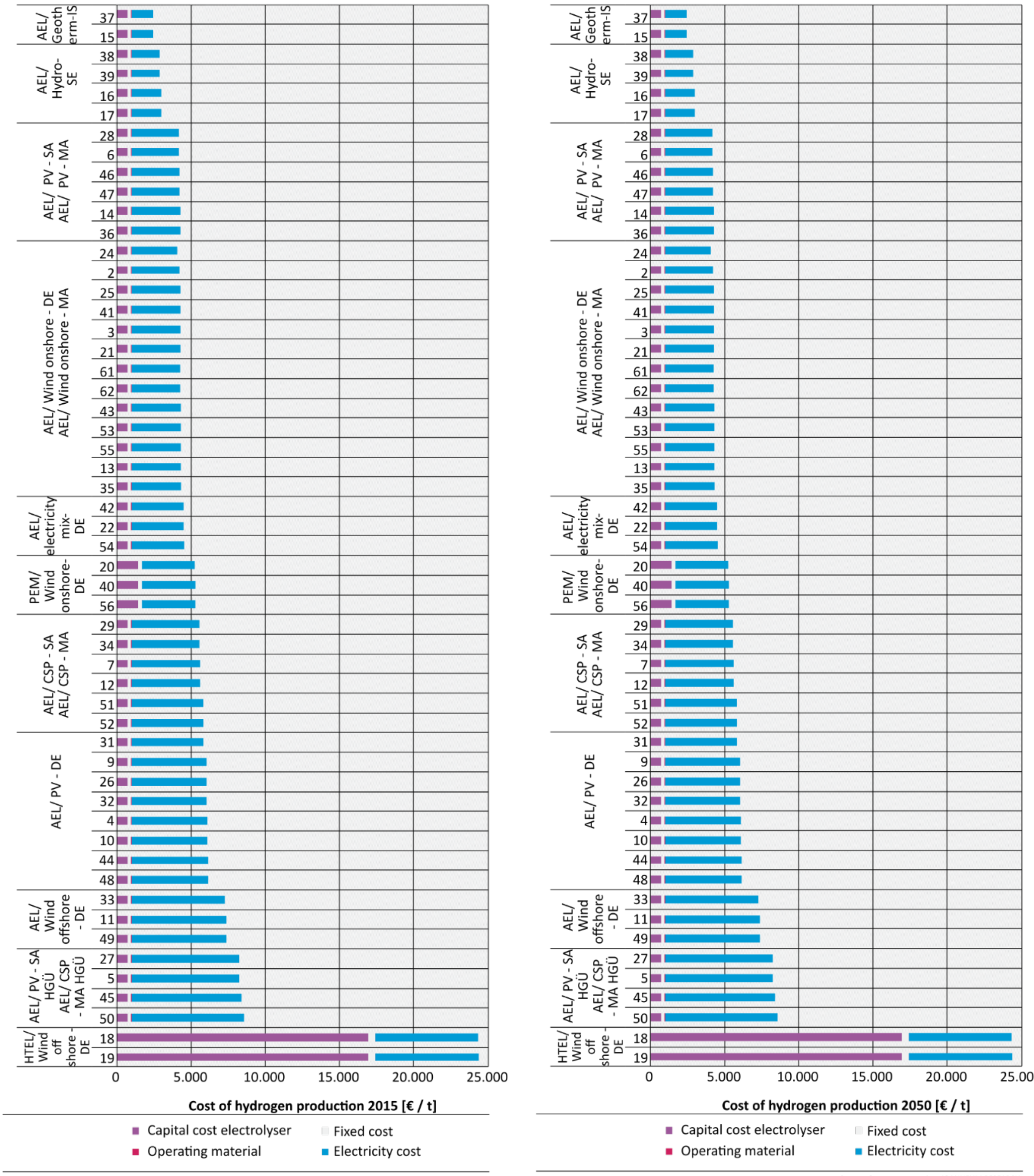
Table 40: Costs of electrolyser operating materials

Fuel	2015	2050	Source
Treated water	2 €/m³	3.4 €/m³	Billig 2016
KOH	220 €/t	220 €/t	BLS 2019

Figure 79 shows the specific hydrogen production costs in [€/t] hydrogen sorted by amount for 2015 and 2050 for the 54 supply paths (as described above, under the assumption that the electricity from the allocated power source is fed to the lectolyzer for more than 8.000 full load hours – with no electricity storage considered). The range of results in 2015 extends from 2,500 to 24,500 €/t hydrogen, with costs for the majority of the paths ranging between 4,200 and 6,200 €/t. In the reference year 2050 the costs are between 2,500 and 6,500 €/t hydrogen, with the majority of the paths with less than 5,500 €/t. Small differences in hydrogen costs in paths using the same power source and electrolysis technology result from the process integration of the electrolysis and synthesis plants in the supply paths.

As Figure 79 shows, electricity costs have by far the greatest influence on the costs of hydrogen supply both in 2015 and 2050 - with the exception of hydrogen production using high-temperature electrolysis in 2015, for which the capital costs of the electrolysis plant dominates. The hydrogen cost ranking is therefore based on the electricity cost ranking, with the lowest cost of hydrogen from geothermal electricity in Iceland and hydroelectric electricity in Sweden. The highest costs, apart from the already mentioned paths with high-temperature electrolysis, are for hydrogen with electricity from offshore wind power in Germany or with PV and CSP electricity from Saudi Arabia and Morocco, which is transmitted to Germany via HVDC. For all paths, Figure 79 shows a significant reduction in capital costs for electrolysis in the reference year 2050. This reduction is most noticeabale in the case of high-temperature electrolysis, due to the reduction of the specific investment costs described above and the significantly longer useful lifetime compared to the reference year 2015. Nevertheless, even in 2050 these paths will still be those with the highest hydrogen costs with electricity from offshore wind farms.

Figure 79: Specific costs of hydrogen production in 2015 and 2050 [€/t]



Source: Own representation, JOANNEUM RESEARCH

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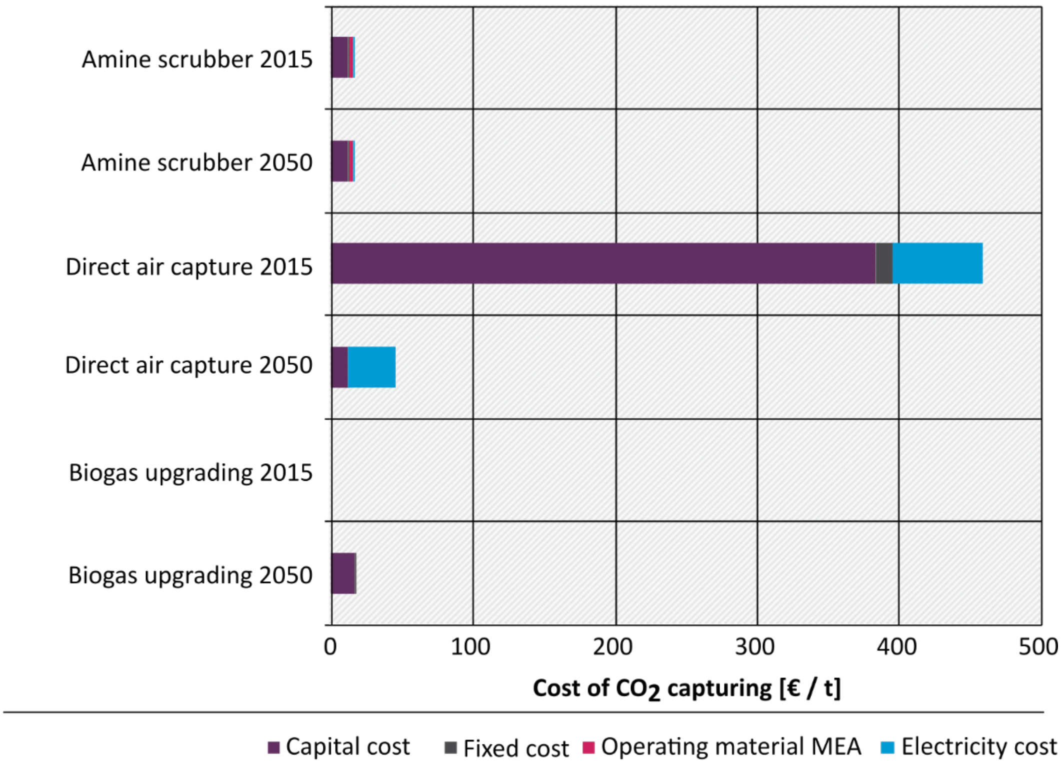
6.2.1.3 CO_2 supply

A carbon dioxide feed is used in 43 of the 62 supply paths studied for the synthesis of storable energy carriers. The cost estimate distinguishes between three different CO_2 capture processes: CO_2 capture from flue gas of industrial facilities and power plants with amine scrubbing, CO_2 capture from the air (Direct Air Capture, DAC), and CO_2 from biogas upgrading. The main factors influencing the specific CO_2 supply costs are the plant capital costs, operating materials and energy costs.

Flue gas scrubbing with monoethanolamine (MEA) is nowadays a standard industrial process in flue gas cleaning. The investment costs of approx. 6 €/t CO_2 (Albrecht 2016) will not change until 2050. The costs for the operating material MEA change only slightly from about 3 €/t CO_2 until 2050 (BLS 2019). For DAC, the cost data used (Viehbahn 2018) were derived from information provided by the technology companies Climeworks and Carbon Engineering, which currently assume specific CO_2 capture costs of 600 USD/t CO_2 and in future 100 USD/t CO_2 (including capital, electricity and heat costs). DAC's energy requirements were estimated using information from Climeworks (on direct request from the company). The electricity costs were calculated on the basis of the industry electricity price in Germany. The heat demand is covered in all supply paths by process integration with free of charge excess heat from the synthesis plant. Therefore, the costs of CO_2 capture shown here are lower than those in the literature by the heat costs (based on natural gas price 9 €/GJ). This also applies to CO_2 capture with MEA scrubbing and biogas upgrading. No costs were calculated for CO_2 from biogas upgrading as a by-product of biomethane production in 2015. For 2050 a price was assumed for CO_2 from biogas due to an expected market value of CO_2, which is based on the costs of CO_2 capture from flue gases of the cement industry calculated in this study.

Figure 80 shows the costs for CO_2 supply in 2015 and 2050 for the CO_2 capture technologies MEA scrubbing, DAC and biogas upgrading with their breakdown into capital costs, fixed costs, costs for the operating material MEA and electricity costs. The CO_2 costs for DAC in 2050 are also significantly higher than the CO_2 costs of MEA scrubbing, despite the comparable capital costs, due to the higher electricity consumption.

Figure 80: Specific costs of CO_2 capture in 2015 and 2050 [€/t] CO_2



Source: Own representation, JOANNEUM RESEARCH

6.2.1.4 Biomass supply

Biomass is used in 17 of 62 supply paths in Biomass-to-Liquid (BtL) and Power-Biomass-to-Liquid (PBtL) plants. The cost data used for the reference year 2015 for the different types of biomass are summarised below.

Table 41: Costs of wood and straw

Biomass	Location	€/t (2015 = 2050)
Straw	Germany	63
Pellets short rotation coppices	Sweden	270
Pellets short rotation coppices	Germany	230
Residual forest wood	Sweden	77

Table 42: Costs of biogas substrates

Biomass	Location	€/t (2015)	€/t (2050)
Bio-waste	Germany	0	44
Green waste	Germany	0	39
Maize	Germany	142	200
Liquid manure	Germany	11	11

6.2.2 Total costs for the supply paths and influencing factors

The specific production costs [€/GJ] in the reference year 2015 were determined for the final energy carriers – Fischer-Tropsch (FT) fuels, methanol, SNG, biomethane and hydrogen – and compared with the costs (excluding taxes) of the corresponding fossil reference products petrol, diesel and CNG.

6.2.2.1 FT Fuels

In line with the presentation of results of the LCA, the results of the cost estimation for the FT fuels are presented separately for the electricity-based PtL and the biomass-based (P)BtL paths. This is due to the different technological readiness level (TRL) of the Fischer-Tropsch synthesis with hydrogen and CO_2 and the biomass-based synthesis processes.

6.2.2.1.1 Electricity-based FT- fuels

For conciseness, only the numbers of the supply paths are given in the following result presentations, reference is made here to Table 17 in which the electricity-based supply paths for FT fuel (PtL) are listed.

In Figure 81 the results of the cost estimate of the electricity-based 17 Fischer-Tropsch paths (PtL synthesis) for the reference year 2015 are shown. The contain the contributions of capital costs, fixed costs as well as costs for operating materials of the synthesis plant, hydrogen supply costs, costs for CO_2 capture and costs for the transport of the products. The costs of hydrogen supply and CO_2 capture which were presented in detail in the previous chapters 6.2.1.2 and 6.2.1.3 are shown here as aggregated costs.

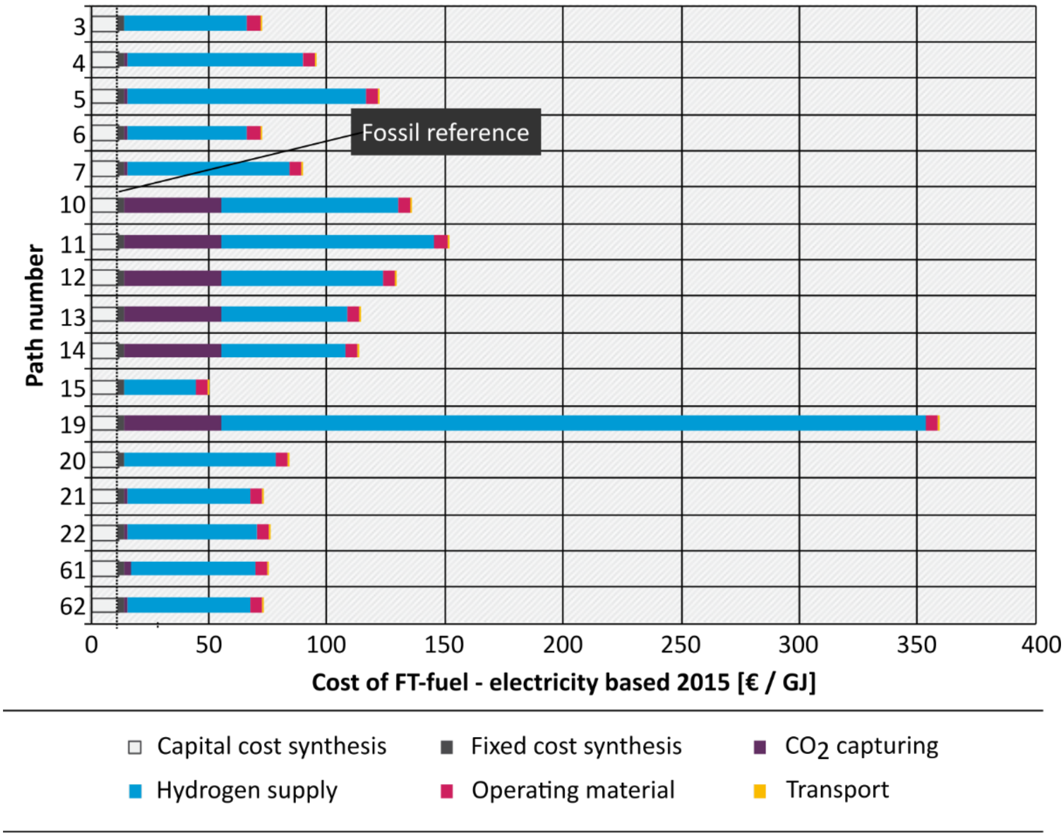
The cost of the fossil reference for the reference year 2015 (approx. 12 €/GJ) is based on the stock market price of petrol over the last 5 years of 1.4 €/Gallon or 0.37 €/l. As described above, the external climate costs are not taken into account in this study, neither for the supply paths studied nor for the fossil reference. The petrol stock market price provides the benchmark for a fossil fuel available in 2015. For the reference year 2050, the cost estimates of the supply paths examined are compared with a notional petrol stock exchange price based on this as a benchmark.

The estimated cost of electricity-based FT fuels in the reference year 2015 is between 49 and 151 €/GJ, with the exception of path 19 at around 360 €/GJ. The lowest cost is for supply path 15 in Iceland, with hydrogen based on electricity from geothermal sources and CO_2 capture also with electricity from geothermal sources. Path 19 has by far the highest costs, due to the high cost of electricity generation with offshore wind power plants and the high capital cost of high-temperature electrolysis, which has a very short lifetime in 2015 (about 10,000 h).

In all paths, the costs for hydrogen supply and thus the electricity costs for hydrogen production represent the largest share of costs, while the costs for the synthesis plant have hardly any influence. The ranking of the paths according to the costs is therefore basically a ranking by the electricity costs. In addition, paths 10 to 14 and 19 reflect the high investment required for CO_2 capture from air (DAC). The costs of CO_2 capture from industrial flue gases as well as from biogas in the other supply paths play a much smaller role. Path 22 with electricity from the German mix (industry electricity price) and CO_2 from a lignite-fired power plant as the path with the highest greenhouse gas emissions in the LCA has comparatively low costs at 76 €/GJ.

A comparison of paths 5 and 6 shows that transporting the liquid energy carrier produced abroad (in this case in Saudi Arabia) by tanker to Germany (path 6) is much cheaper from a cost perspective than transporting the electricity generated abroad using HVDC transmission for the production of FT fuel in Germany (path 5). The assumptions for transport are that the costs for HVDC transmission per kWh of electricity in 2050 will be the same as in 2015, and for transport per tonne of liquid fuel in tankers will increase by about 25% (2015: 14 €/t; 2050: 17.4 €/t).

Figure 81: Cost of electricity-based FT fuels (PtL) 2015



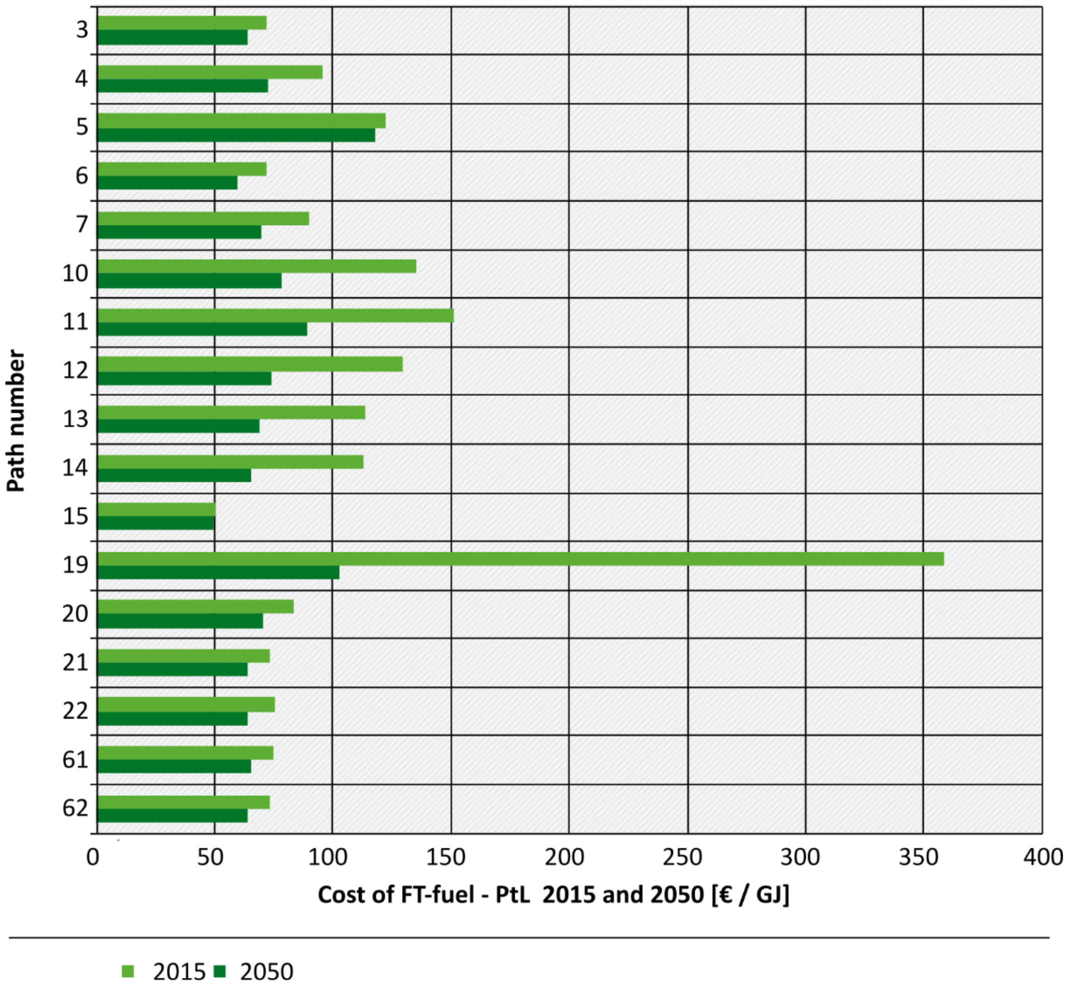
Source: Own representation, JOANNEUM RESEARCH

Figure 82 shows the results of the cost estimation of the 17 electricity-based FT-PtL supply paths for 2015 and 2050. Compared to 2015, the costs will decrease by 0 to 70% by 2050. No change is seen in path 15 (electricity from geothermal energy in Iceland), the largest cost reduction is seen in path 19 (electricity offshore wind power and high temperature electrolysis) due to significantly lower capital costs for the hydrogen supply in 2050.

The cost reduction for the other paths is due to the change in the factors influencing the costs of electricity, hydrogen and CO_2 supply described in Chapter .The capital costs of the synthesis plants will not change in 2050 compared to 2015. Those paths whose costs in 2015 are in the range of 70 to 75 €/GJ FT fuel in 2015 are about 10 to 15% lower in 2050 in a range of 60 to 65 €/GJ. In paths 10 to 14 with CO_2 capture from the air, the costs will be reduced by about 40% due to the significantly lower capital costs of DAC. The comparison of paths 5 and 6 shows that the cost difference between path 6 with transport of the liquid energy carrier produced abroad (here in Saudi Arabia) by tanker to Germany and path 5 with transport of the electricity produced abroad by HVDC to Germany remains roughly the same.

All cost results for the reference year 2050, with the exception of path 5 and 19, are below 90 €/GJ. 90 €/GJ correspond to 2.8 €/l petrol production costs (excluding taxes). This is 7.5 times the petrol price in 2015.

Figure 82: **Cost of electricity-based FT-fuels (PtL) 2015 and 2050**

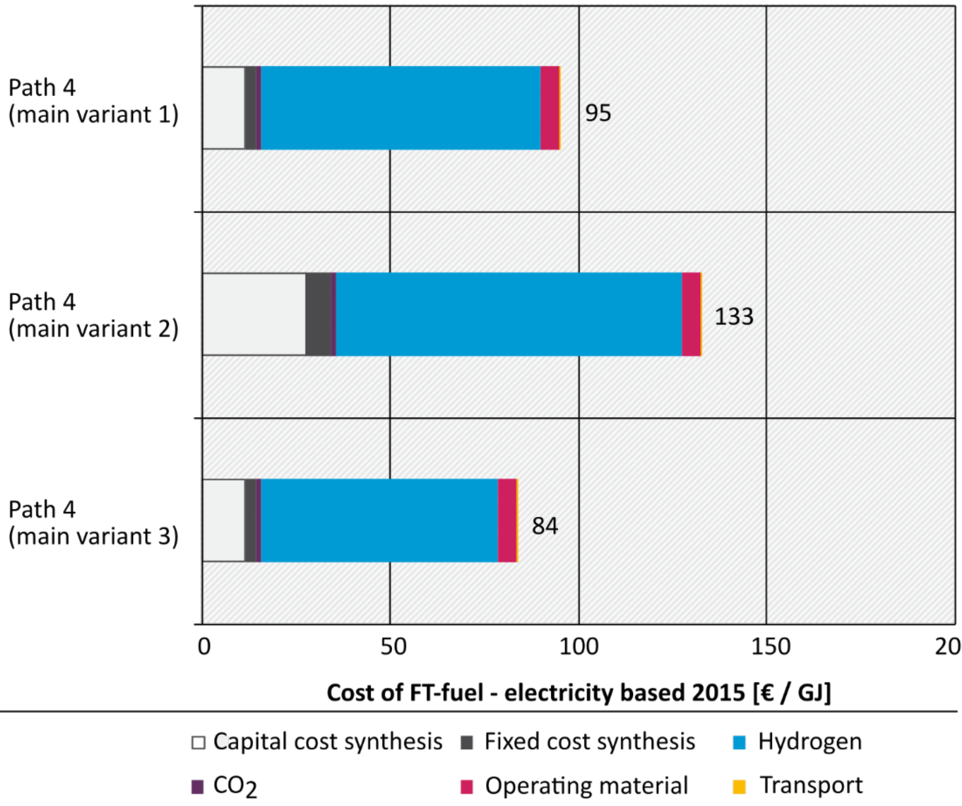


Source: Own representation, JOANNEUM RESEARCH

As already explained in Chapter 6.1.1, a sensitivity analysis, using supply path 4 (FT/PVground/AEL/cement/trucks/D) for the reference year 2015 compares the dependence of costs on different annual full load hours of electrolysis, CO_2 capture and of the synthesis plant for three cases: In the main case 1, the electrolysers, CO_2 capture and synthesis plants run the maximum possible annual operating hours (around 8000 full load hours) and are arithmetically supplied from the assigned power source. In main case 2, electrolysers, CO_2 capture and synthesis plants run only the number of operating hours corresponding to the full load hours of the assigned power source. In the main case 3, the electrolysers, CO_2 capture and synthesis plants also run the maximum possible annual operating hours, but the power supply from the assigned power source is only calculated according to the operating hours of the power generation plant, the rest of the electricity comes from the grid (with industry electricity prices).

Figure 83 shows the results of these calculations. In the main case 2, the costs even decrease slightly compared to the base case. The reason for this is the lower electricity costs for hydrogen production due to the lower industry electricity price compared to PV electricity. In main case 3 the costs increase by 40%. The reason for this is the higher contribution of the plant infrastructure. The capital costs are assigned to a lower product output at lower full load hours and the same lifetime.

Figure 83: Costs FT fuel path 4 (PtL) 2015 sensitivity full load hours



Source: Own representation, JOANNEUM RESEARCH

6.2.2.1.2 Predominantly biomass-based FT fuels

As for the electricity-based paths in Chapter 6.2.2.1.1 only the numbers of the supply paths are listed in the following diagrams. The biomass-based supply paths for FT fuel (BtL, PBtL) are described in Table 19.Table 19 In contrast to the electricity-based supply paths for FT fuels, the biomass-based paths do not incur any costs for CO_2 capture, but do incur costs for biomass and transport.

Figure 81 shows the results of the cost estimation of the seven biomass-based Fischer-Tropsch paths ((P)BtL synthesis) for the reference year 2015. Included are the contributions of capital costs, fixed costs, biomass costs and costs for operating materials of the synthesis plant, hydrogen supply costs and costs for the transport of the products. The costs of hydrogen supply and biomass supply are described in detail in chapters 6.2.1.2and 6.2.1.4 and are shown here as aggregated.

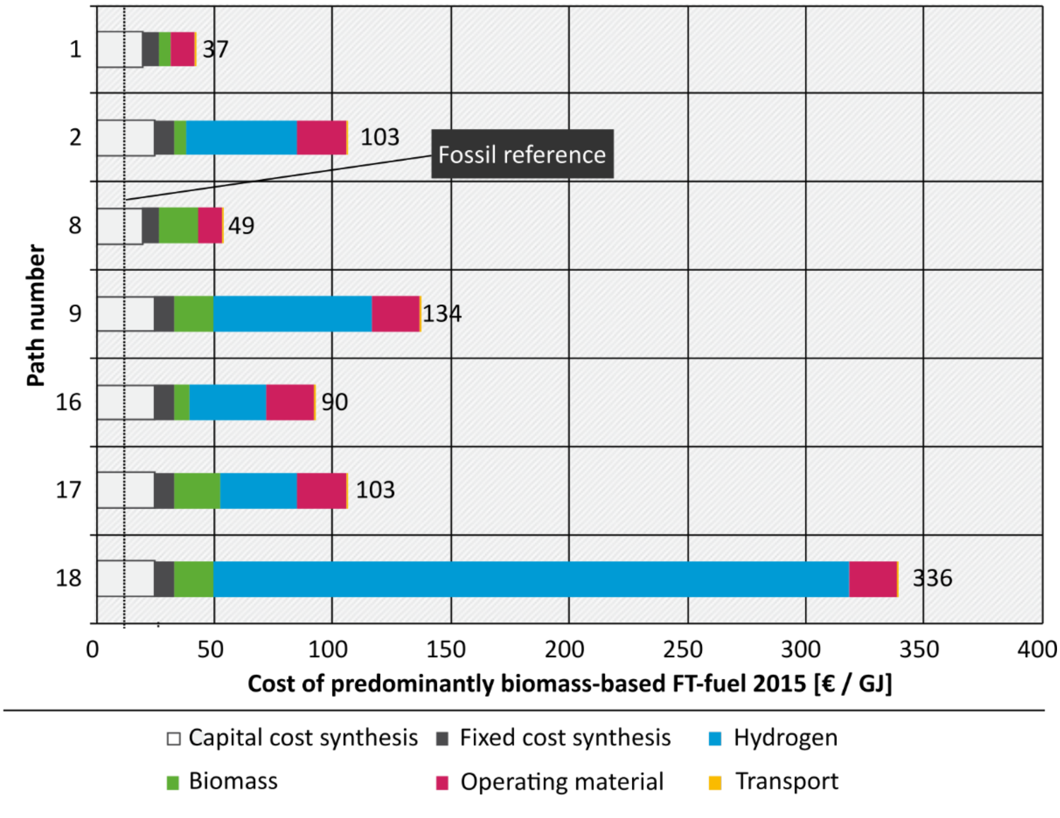
The costs of the fossil reference for the reference year 2015 (approx. 12 €/GJ) are assumed to be the same as for the electricity-based FT fuels in 6.2.2.1.1.

The estimated costs of the biomass-based FT fuels in the reference year 2015 are between 37 and 134 €/GJ, with the exception of path 18 at about 336 €/GJ. In all paths in which hydrogen is used, the costs of hydrogen supply and thus the electricity costs for hydrogen production represent the largest share of the costs. The ranking of the paths by cost therefore reflecs the ranking of electricity costs.

Supply paths 1 and 8, which do not use hydrogen and also use a less expensive synthesis plant, are the most cost-effective paths from a cost perspective. Path 1, using straw, is somewhat cheaper than path 8, which uses poplar wood from short rotation coppices. Path 18 has, analogous to path 19, by far the highest costs due to the high cost of electricity generation with offshore wind power and the high capital costs of high-temperature electrolysis. The comparison of paths 16 and 17 shows the relatively small cost difference when using forest residues compared to poplar wood from short rotation coppices in Sweden, despite the more than threefold costs of biomass.

It is also interesting to compare the costs of paths 1 and 2 or paths 8 and 9, in which the same biomass is used respectively - in paths 1 and 8 in a Biomass-to-Liquid (BtL) process and in paths 2 and 9 in a combined Power&Biomass-to-Liquid (PBtL) process. The main difference is the use of additional hydrogen in the PBtL process in order to use more carbon from the biomass compared to the BtL process. However, the more efficient use of biomass is offset by the high costs of hydrogen supply, so that the PBtL paths have costs that are about 2.7 times higher than comparable BtL paths.

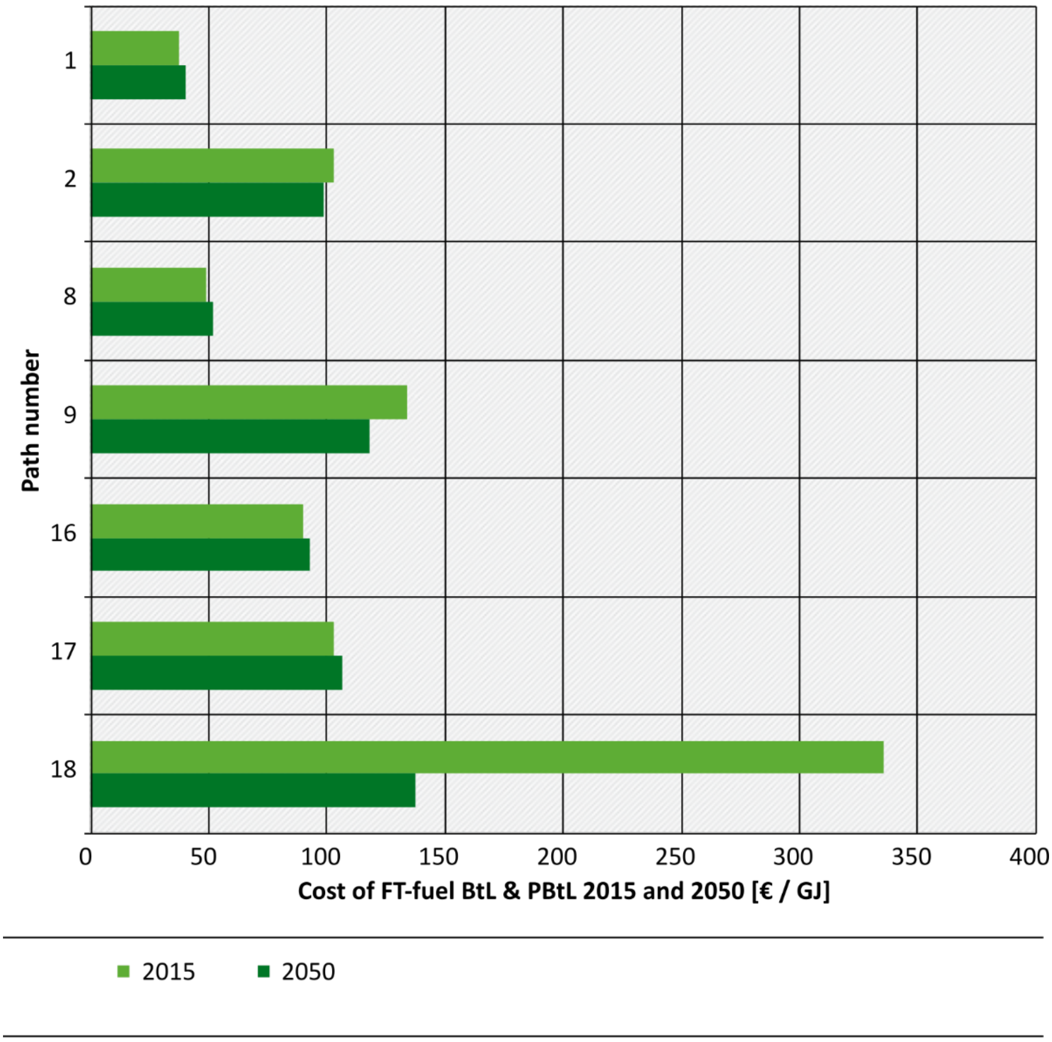
Figure 84: Costs of predominantly biomass-based FT fuels (BtL, PBtL) 2015



Source: Own representation, JOANNEUM RESEARCH

Figure 85 shows the results of the cost estimation of the seven FT-BtL and PBtL supply paths for 2015 and 2050. The capital costs of the synthesis plants will not change in 2050 compared to 2015. The largest cost change, with a reduction of 57%, is seen in path 18 (with electricity from offshore wind power and hydrogen from high-temperature electrolysis) due to significantly lower capital costs for hydrogen supply in 2050. The minor cost changes for the other paths are mainly due to the change in the factors influencing the costs of electricity and hydrogen supply and of fuels (Selexol® , oxygen for gasification) described in Chapter 6.2.1

Figure 85: Cost of predominantly biomass-based FT-fuels (BtL, PBtL) 2015 and 2050



Source: Own representation, JOANNEUM RESEARCH

6.2.2.2 Methanol

As for the FT fuels and in line with the results of the life cycle assessment, the results of the cost estimate for methanol are considered separately for the electricity-based and the biomass-based supply paths due to the different technology readiness levels of methanol synthesis with hydrogen and CO_2 and the biomass-based processes (Chapter 5.3.3.2).

6.2.2.2.1 Results for current based paths

For conciseness, only the numbers of the supply paths are given in the following result presentations, reference is made here to Table 21 in which the electricity-based supply paths for methanol (PtL) are listed.

Figure 86 shows the results of the cost estimation of the 14 electricity-based methanol paths (PtL synthesis) for 2015 with the shares of capital costs, fixed costs as well as costs for operating materials of the synthesis plant, hydrogen supply costs, costs for CO_2 capture and costs for the transport of the product. As costs of hydrogen supply and CO_2 capture are presented in detail in chapters 6.2.1.2 and 6.2.1.3 they are shown here only as aggregated costs.

The cost of the fossil reference for the reference year 2015 (approx. 20 €/GJ) is based on a methanol trade price of approx. 400 €/t methanol over the last 5 years. As already described for FT fuels, the external climate costs are not considered in this study, neither for the supply paths investigated nor for the fossil reference.

The estimated costs of the electricity-based methanol paths in the reference year 2015 are between €46 and €152 per GJ. The lowest cost is for supply path 37 in Iceland with hydrogen production and CO_2 capture with geothermal electricity. Path 33 has the highest cost, due to the high cost of electricity generation with offshore wind power.

In all paths, the costs for hydrogen supply and thus the electricity costs for hydrogen production represent the largest share of costs, while the costs for the synthesis plants have hardly any influence. The ranking of the paths according to the costs therefore reflects the ranking of electricity costs. In addition, paths 32 to 36 reflect the high investment required for CO_2 capture from the air (DAC). The costs of CO_2 capture from industrial flue gases as well as from biogas in the other supply paths play a much smaller role. Path 42 with electricity from the German mix (industry electricity price) and CO_2 from a lignite-fired power plant as the path with the highest greenhouse gas emissions in the LCA has comparatively low costs of 72 €/GJ.

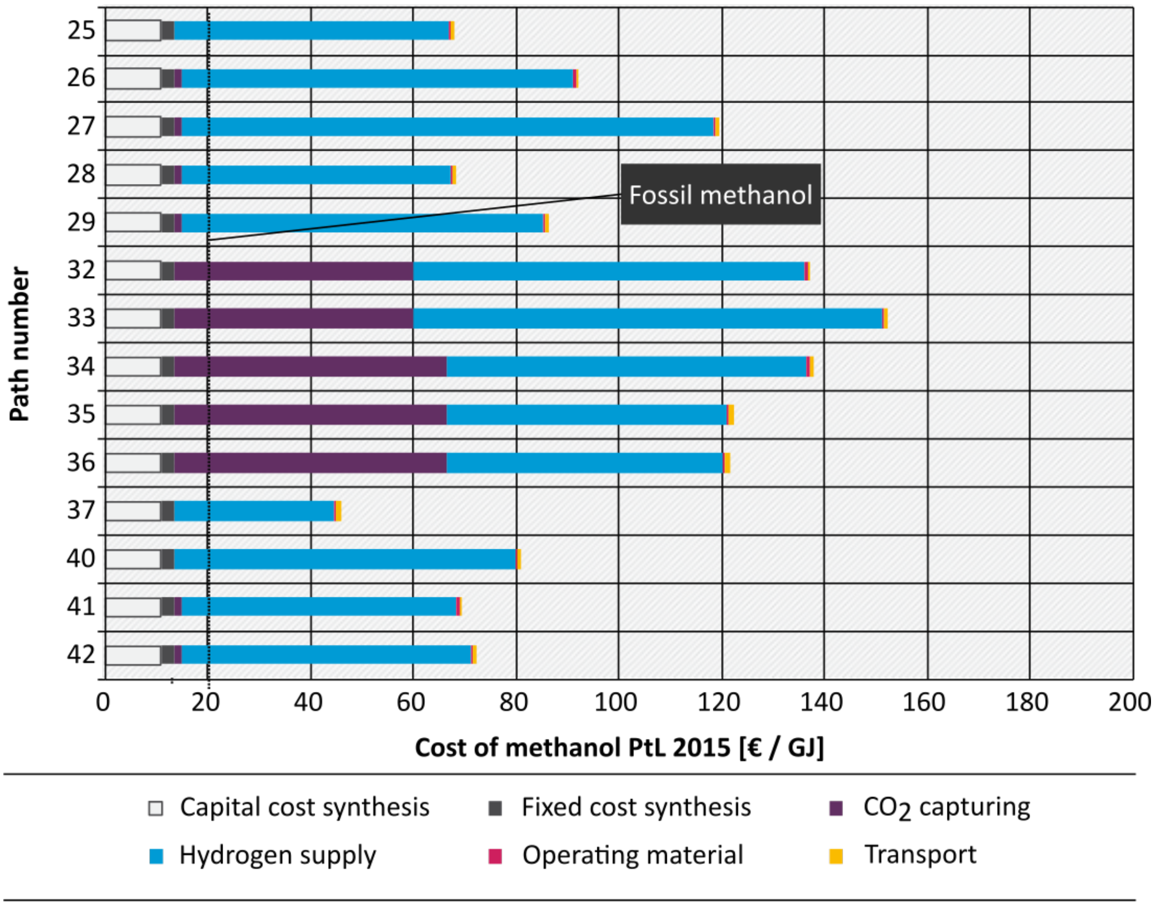
A comparison of paths 27 and 28 shows that transporting the liquid energy carrier produced abroad (in this case in Saudi Arabia) by tanker to Germany (path 28) is much cheaper than transporting the electricity generated abroad using HVDC transmission for the production of methanol in Germany (path 27). The assumptions for transport are the same as for FT fuel, namely that the costs for HVDC transmission per kWh of electricity in 2050 will be the same as in 2015 and that the costs for transport per tonne of methanol in tankers will increase by about 25% by 2050.

Figure 87 shows the results of the cost estimates of the 14 electricity-based methanol PtL supply paths for 2015 and 2050. Compared to 2015, the costs will decrease by 0 to 45% by 2050. No change can be seen in path 25 (electricity from geothermal energy in Iceland). The largest cost reduction is seen in paths 32 to 36 due to significantly lower capital costs in 2050 for CO_2 capture with DAC.

The cost reductions for the other paths are mainly due to the change in the factors influencing the costs of electricity, hydrogen and CO_2 supply described in Chapter 6.2.1. The capital costs of the synthesis plants will not change in 2050 compared to 2015. Those paths whose costs are in the range of 70 to 90 €/GJ of methanol in 2015 will be approximately 10 to 15% lower in 2050, in the range of 60 to 70 €/GJ. In paths 32 to 36 with CO_2 capture from the air, costs are reduced by about 45% due to the significantly lower capital costs of DAC. The comparison of paths 27 and 28 shows that the cost difference between path 28 with transport of the methanol produced abroad (here in Saudi Arabia) by tanker to Germany and path 27 with transport of the electricity produced abroad by HVDC to Germany remains roughly the same.

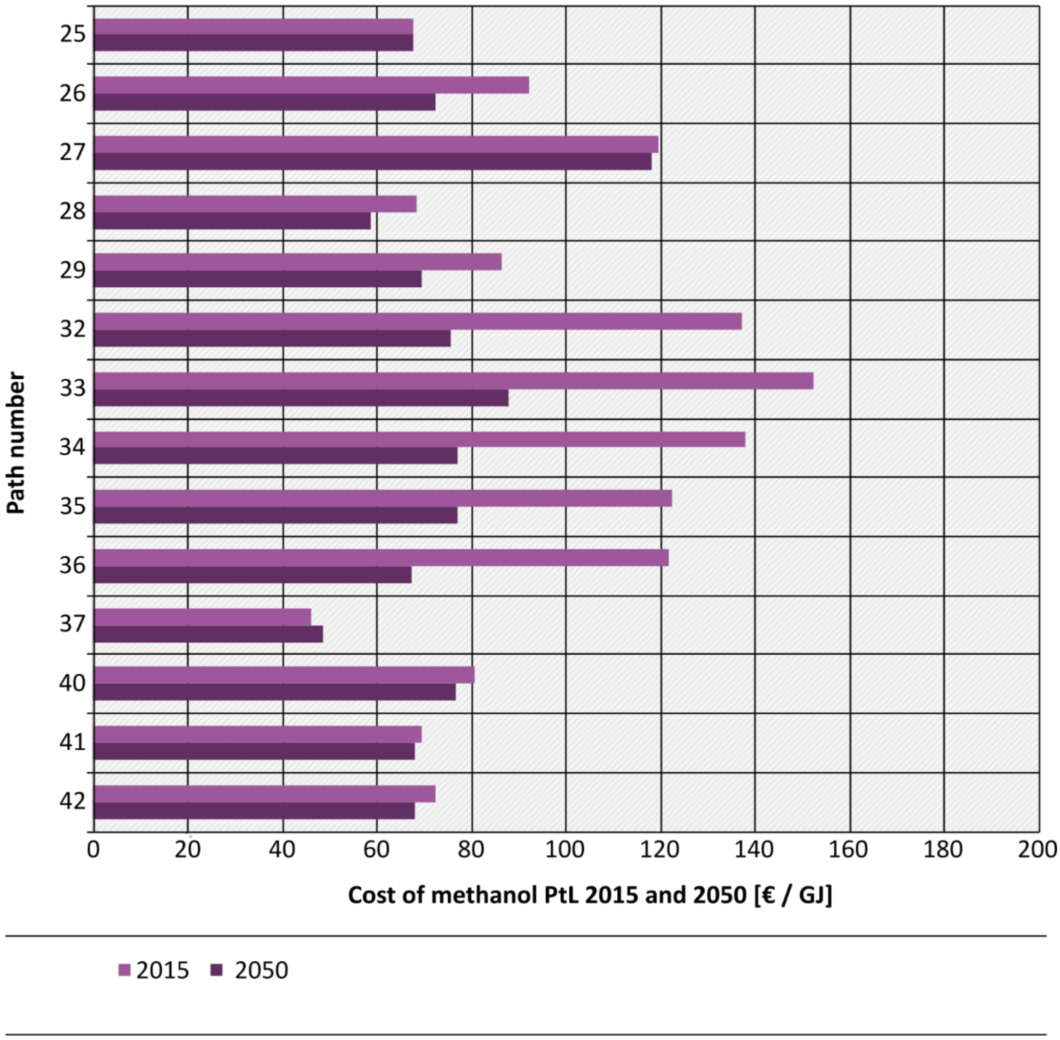
All cost results are below 90 €/GJ in the reference year 2050, with the exception of path 27. 90 €/GJ. That corresponds to methanol production costs (without taxes) price of approx. 1.800 €/t. This is 4.5 times the methanol price in 2015.

Figure 86: Cost of electricity-based methanol (PtL) 2015



Source: Own representaation, JOANNEUM RESEARCH

Figure 87: **Cost of electricity-based methanol (PtL) in 2015 and 2050**

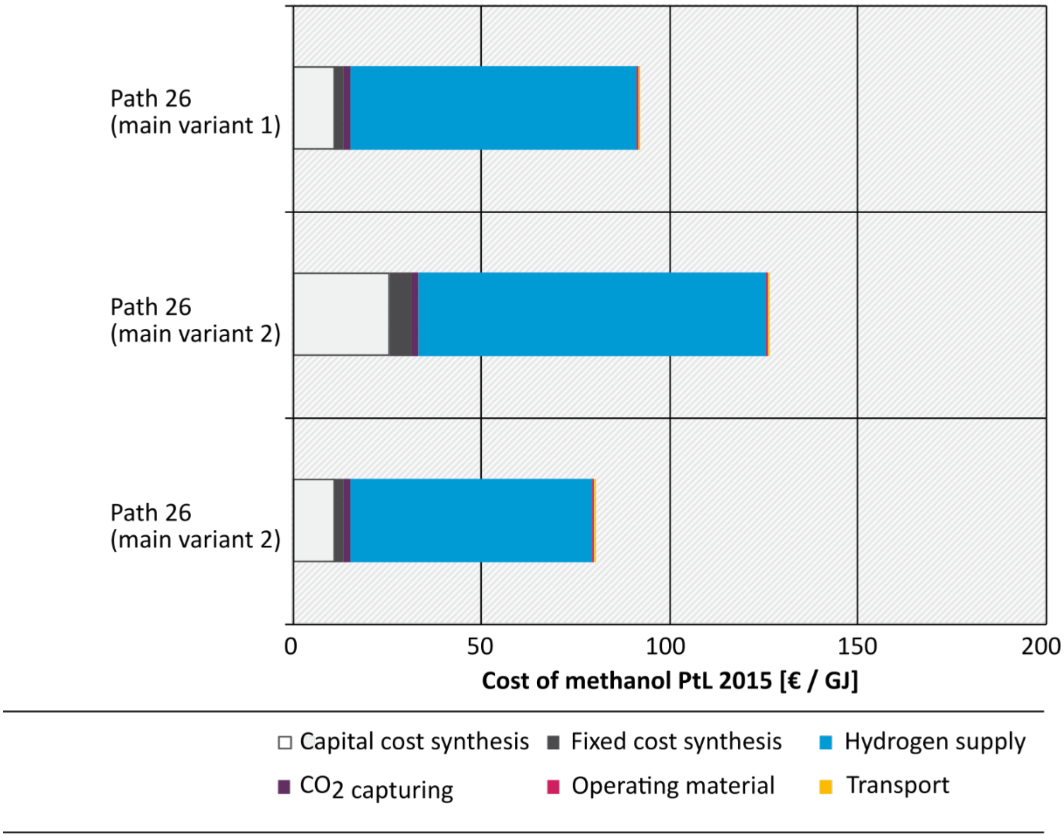


Source: Own representation, JOANNEUM RESEARCH

As already explained in chapter 6.1.1 and analogous to chapter 6.2.2.1.1of the FT fuels, a sensitivity analysis, using the example of supply path 26 (methanol/PtL/PVground/AEL/cement/LKW_D) for the reference year 2015, compares the dependence of methanol costs on different annual hours of electrolysis, CO_2 capture and synthesis plant for the three main cases.

Figure 88 shows the results of these calculations. In the main case 2 the costs increase by about 60%. The reason for this is the higher contribution of the plant infrastructure. The capital costs are assigned to a lower product output at lower full load hours and the same lifetime. In main case 3 the costs even decrease slightly compared to the base case. The reason for this is the lower electricity costs for hydrogen production due to the lower industry electricity price compared to PV electricity.

Figure 88: Cost of methanol path 26 (PtL) 2015 - Sensitivity full load hours



Source: Own representation, JOANNEUM RESEARCH

6.2.2.2.2 Results for biomass-based paths

As for the electricity-based paths in Chapter 6.2.2.2.1only the numbers of the supply paths are listed in the following result illustrations for space reasons. The biomass-based supply paths for methanol (BtL, PBtL) are described in Table 23. In contrast to the electricity-based methanol supply paths, the biomass-based paths do not incur any costs for CO_2 capture, but do incur costs for biomass and transport.

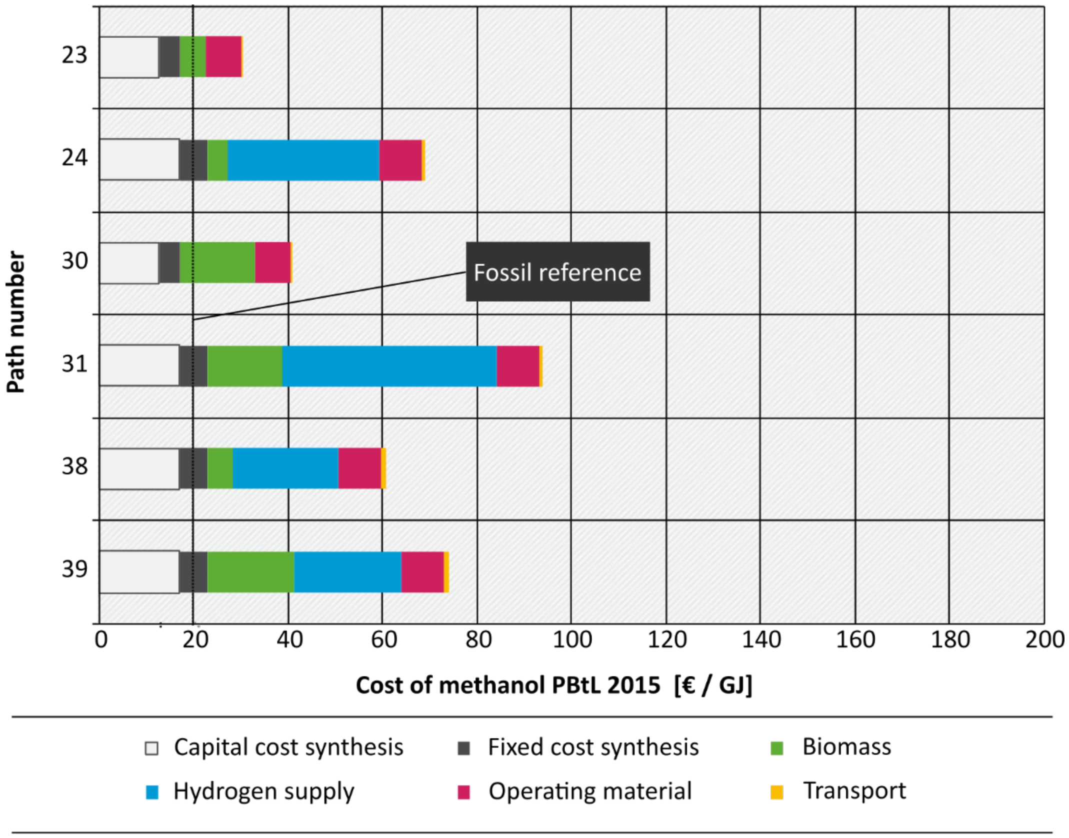
Figure 89 shows the results of the cost estimate for the six biomass-based methanol paths (BtL, PBtL synthesis) for the reference year 2015, with the shares of capital costs, fixed costs, biomass costs and costs for operating materials of the synthesis plant, hydrogen supply costs and costs for transporting the product. The costs of hydrogen supply and biomass supply are described in detail in chapters 6.2.1.2and 6.2.1.4 and are shown here only as aggregated costs.

The estimated costs of the biomass-based methanol paths in the reference year 2015 are between 28 and 152 €/GJ. In all paths where hydrogen is used, the costs for hydrogen supply and thus the electricity costs for hydrogen production represent the largest share of the costs. The ranking of the paths according to cost is therefore based on the ranking of electricity costs.

Supply paths 23 and 30, which do not use hydrogen and also use a less expensive synthesis plant, are the most cost-effective paths. Path 23 with straw as the biomass is slightly better than path 30, which uses poplar wood from short rotation coppices. The comparison of paths 38 and 39 shows the cost difference for using forest residues compared to poplar wood from short rotation coppices in Sweden.

It is also interesting to compare the costs of paths 23 and 24 or paths 30 and 31, where the same biomass is used respectively - in paths 23 and 30 in a Biomass-to-Liquid (BtL) process and in paths 24 and 31 in a combined Power&Biomass-to-Liquid (PBtL) process. The main difference is the use of additional hydrogen in the PBtL process in order to use more of the carbon in the biomass compared to the BtL process. However, the more efficient use of the biomass is offset by the high costs of hydrogen supply, so that the PBtL paths have costs that are about 2.3 times higher than comparable BtL paths.

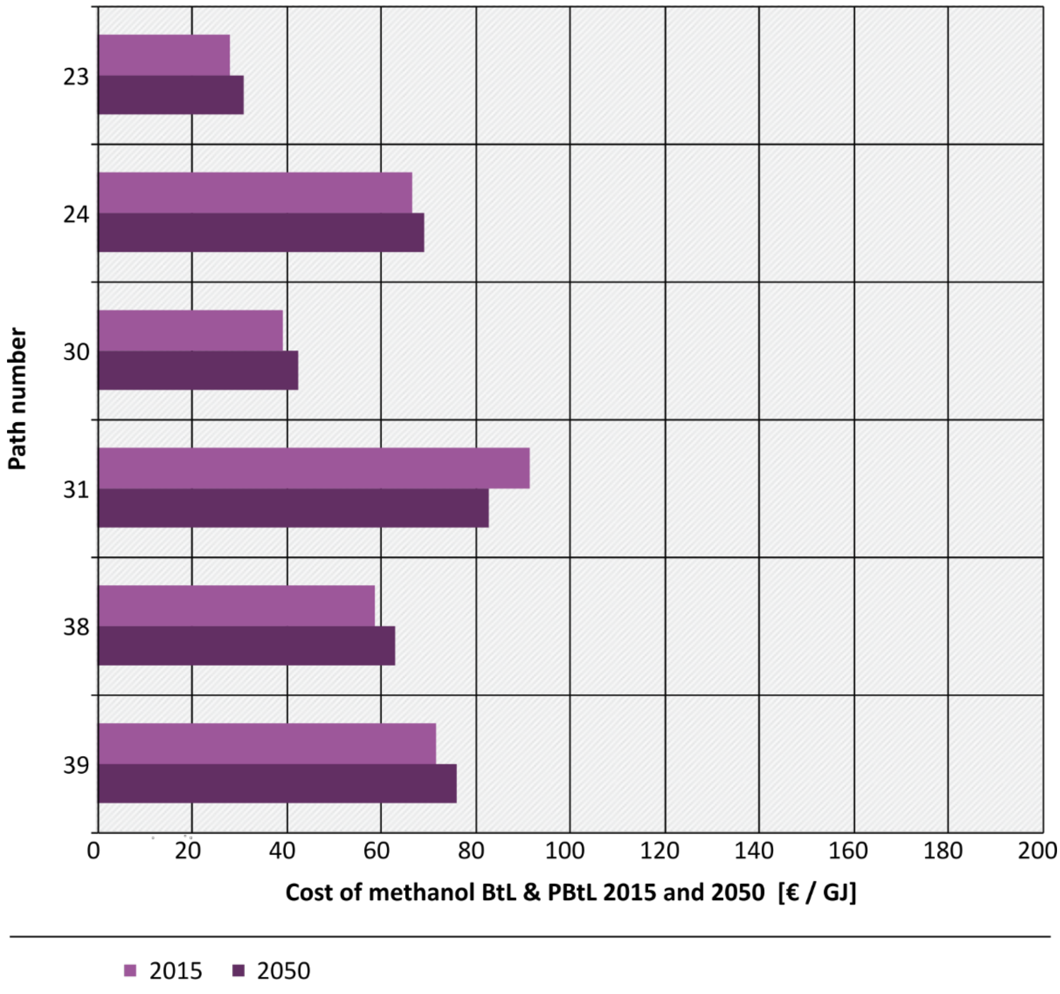
Figure 89: Costs of predominatly biomass-based methanol (BtL, PBtL)2015



Source: Own representation, JOANNEUM RESEARCH

Figure 90 shows the results of the cost estimates for the six methanol BtL and PBtL supply paths for the years 2015 and 2050. Compared to 2015, the costs in the reference year 2050 change only slightly. The minor cost changes are mainly due to the change in the factors influencing the costs of electricity and hydrogen supply and of operating materials (Selexol® , oxygen for gasification) described in Chapter 6.2.1

Figure 90: Costs of predominatly biomass-based methanol (BtL, PBtL) in 2015 and 2050



Source: Own representation, JOANNEUM RESEARCH

6.2.2.3 Synthetic natural gas (SNG)

For conciseness, only the numbers of the supply paths are shown in the following result diagrams. Full descriptions of the SNG supply paths are listed in Table 25.

Figure 91 shows the results of the cost estimation of the twelve SNG paths for the reference year 2015 with the shares of capital costs, fixed costs as well as costs for operating materials of the synthesis plant, hydrogen supply costs, costs for CO_2 capture and costs for the transport of the product. The costs of hydrogen supply and CO_2 capture are presented in detail in chapters 6.2.1.2 and 6.2.1.3 and are shown here as aggregated costs.

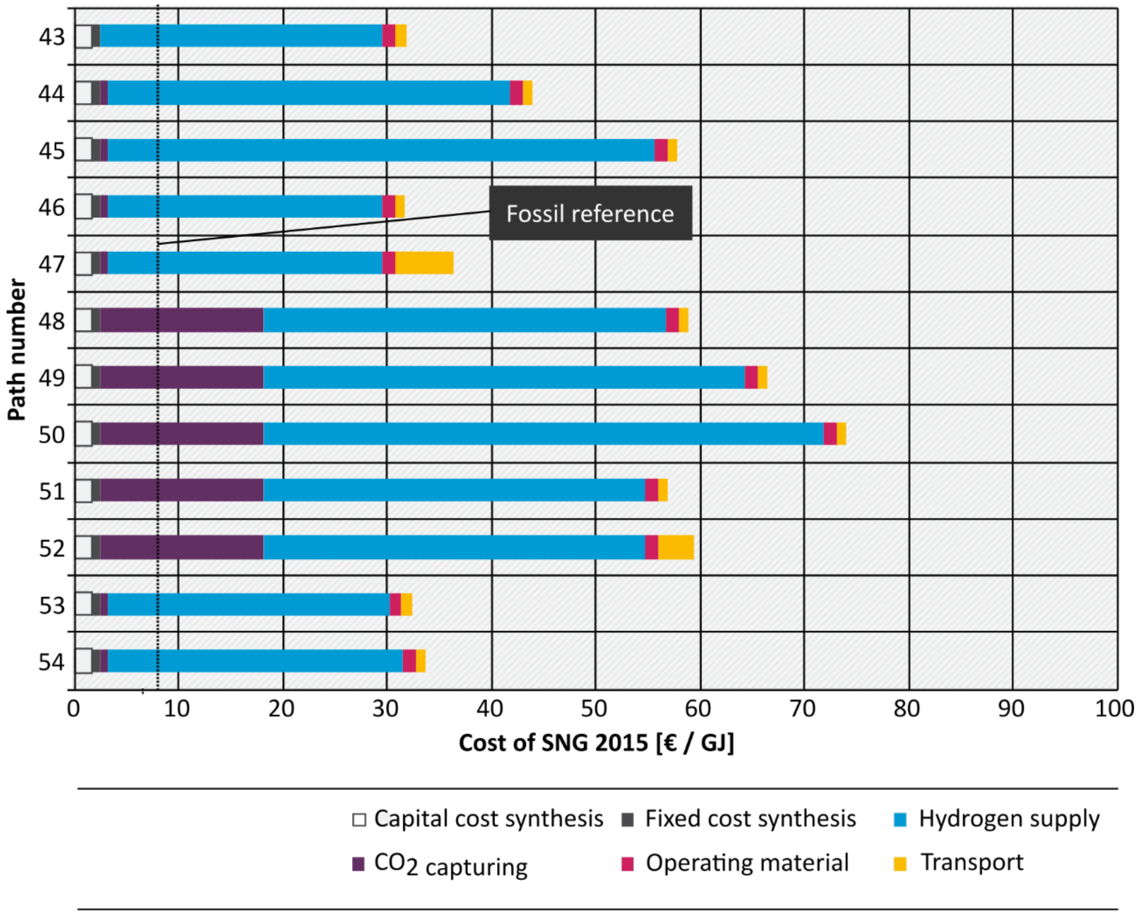
The cost of the fossil reference for the reference year 2015 (approx. 8 €/GJ) is based on an industry natural gas price of approx. 3 cent/kWh. As described above, the external climate costs are not considered in this study, neither for the supply paths investigated nor for the fossil reference.

The estimated costs of the SNG paths in the reference year 2015 are between €32 and €74/GJ. The three supply paths with the lowest costs are: path 43 with electricity from onshore wind power and CO_2 from biogas, path 46 with electricity from PV in Saudi Arabia and CO_2 from the cement industry and SNG transport to Germany by gas pipeline, and path 53 with electricity from onshore wind power and CO_2 from a lignite-fired power plant. Path 50 has the highest costs, due to the high cost of electricity generation with offshore wind power and the high capital cost of CO_2 capture with DAC.

In all paths, the electricity costs for electrolysis represent the largest share of the costs, while the costs for the synthesis plant have hardly any influence. Paths 48 to 52 also reflect the high investment requirement for CO_2 capture from the air (DAC). The ranking of the paths by costs therefore reflects the ranking of the electricity costs.

A comparison of paths 50, 51 and 52 clearly shows, as already shown above for the FT fuel and methanol paths, that transporting the SNG produced abroad (here in Morocco) by gas pipeline or tanker to Germany (paths 51, 52) is cheaper from a cost perspective than transporting the electricity produced abroad by HVDC transmission to Germany for SNG production in Germany (path 50).

Figure 91: Costs of SNG (PtG) 2015

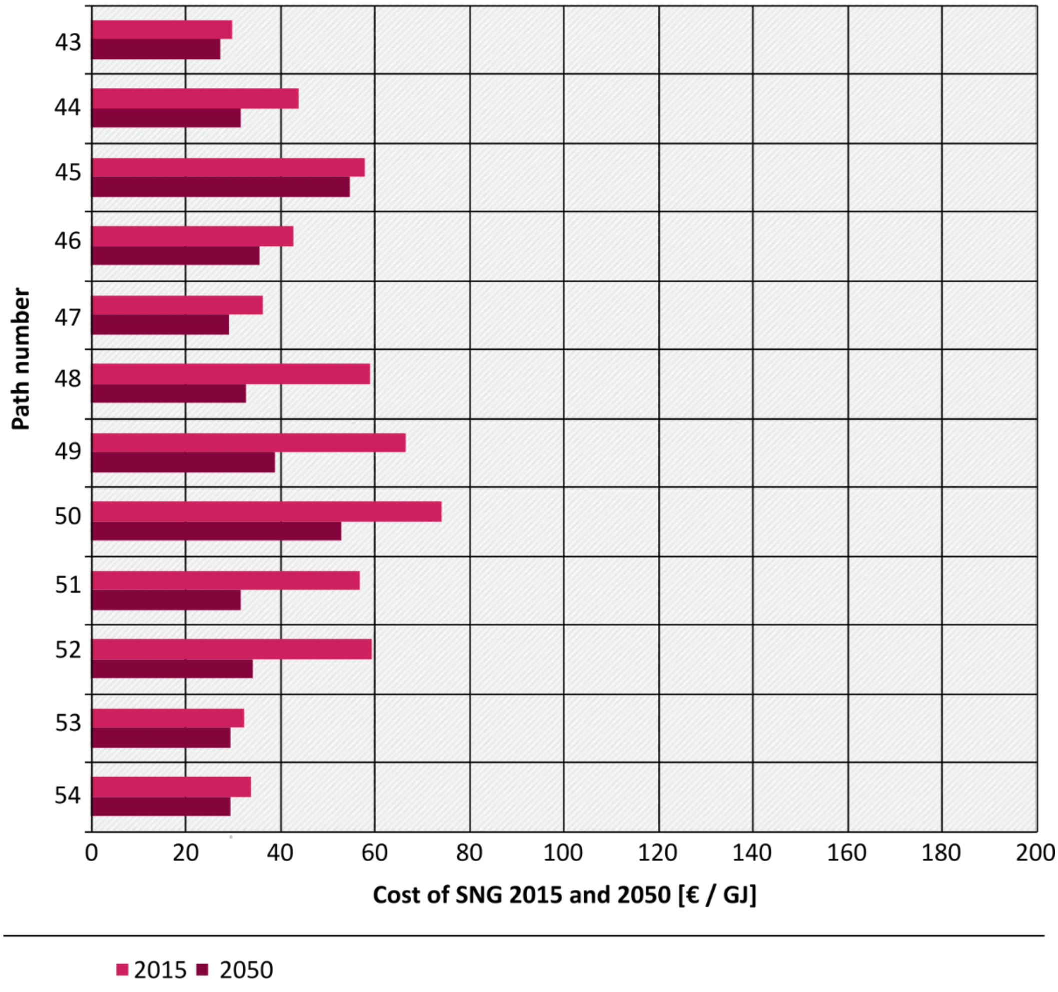


Source: Own representation, JOANNEUM RESEARCH

Figure 92 shows the results of the cost estimation for the 12 SNG supply paths for the years 2015 and 2050. Compared to 2015, the costs are reduced by 5 to 45% by 2050. The cost reduction in all paths is mainly due to the change in the factors influencing the costs of electricity, hydrogen and CO_2 supply described in Chapter 6.2.1. The capital costs of the synthesis plants will not change in 2050 compared to 2015. The smallest change is seen in paths 43, 53 and 54 with electricity from onshore wind power and CO_2 from industrial flue gas sources. The largest cost reduction is seen in paths 48 to 52 due to significantly lower capital costs in 2050 for CO_2 capture with DAC. The comparison of paths 50, 51 and 52 shows that the cost differences described above due to different modes of transport to Germany will roughly persist.

All cost estimations are below 60 €/GJ in the reference year 2050. 60 €/GJ correspond to a notional gas price of approx. 22 cent/kWh. This is 7.5 times the industry natural gas price in 2015.

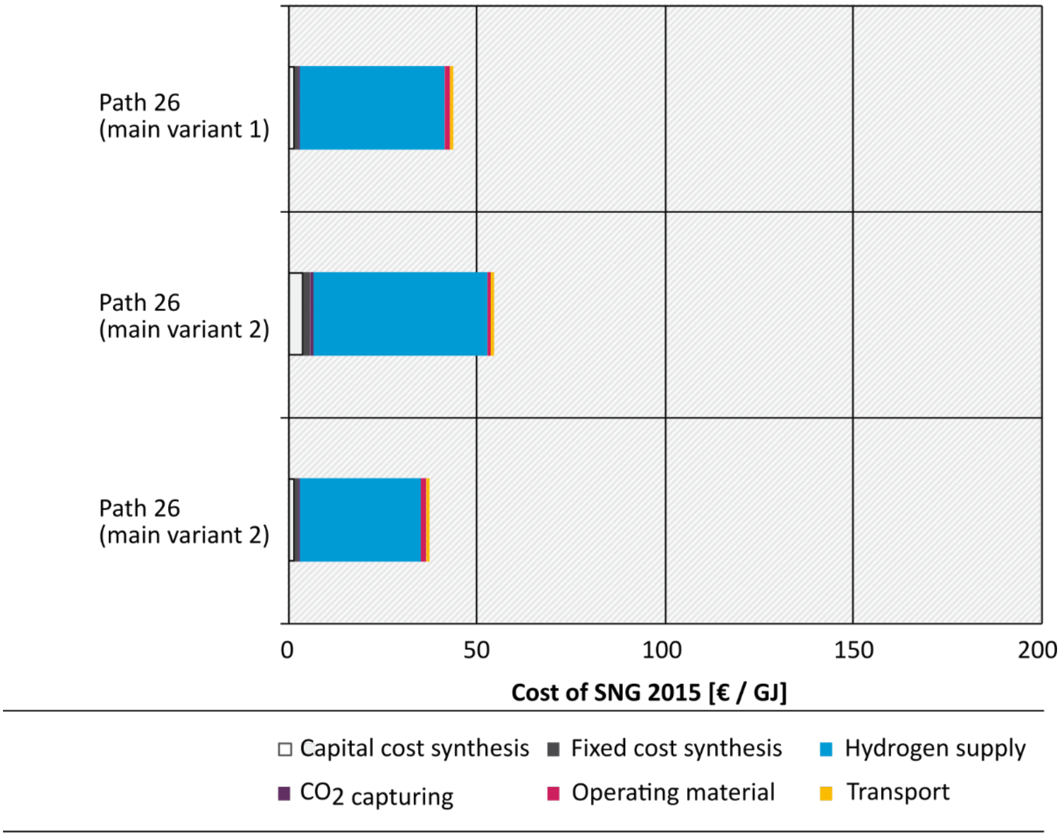
Figure 92: Costs of SNG (PtG) in 2015 and 2050



Source: Own representation, JOANNEUM RESEARCH

As for liquid fuels, a sensitivity analysis for supply path 44 (44_SNG/PtG/PVground/AEL/Cement/Gas Grid (D)_D) analyses the dependence of costs on the different annual full load hours of the electrolysers, CO_2 capture, synthesis plants and electricity generation. The results are presented it in Figure 93. In the main case 2 (electrolysers, CO_2 capture and synthesis plants are operated with the full load hours of the associated power source) the costs increase by 25%. This is due to the higher contribution of the plant infrastructure. The capital costs are assigned to a lower product output at lower full-load hours and the same lifetime. In main case 3 (annual operating hours of the allocated power source, the rest of the electricity from the grid) the costs even decrease slightly compared to main case 1. The reason for this is the lower electricity costs for hydrogen production due to the lower industry electricity price compared to PV electricity.

Figure 93: Costs SNG path 44 2015 - sensitivity full load hours



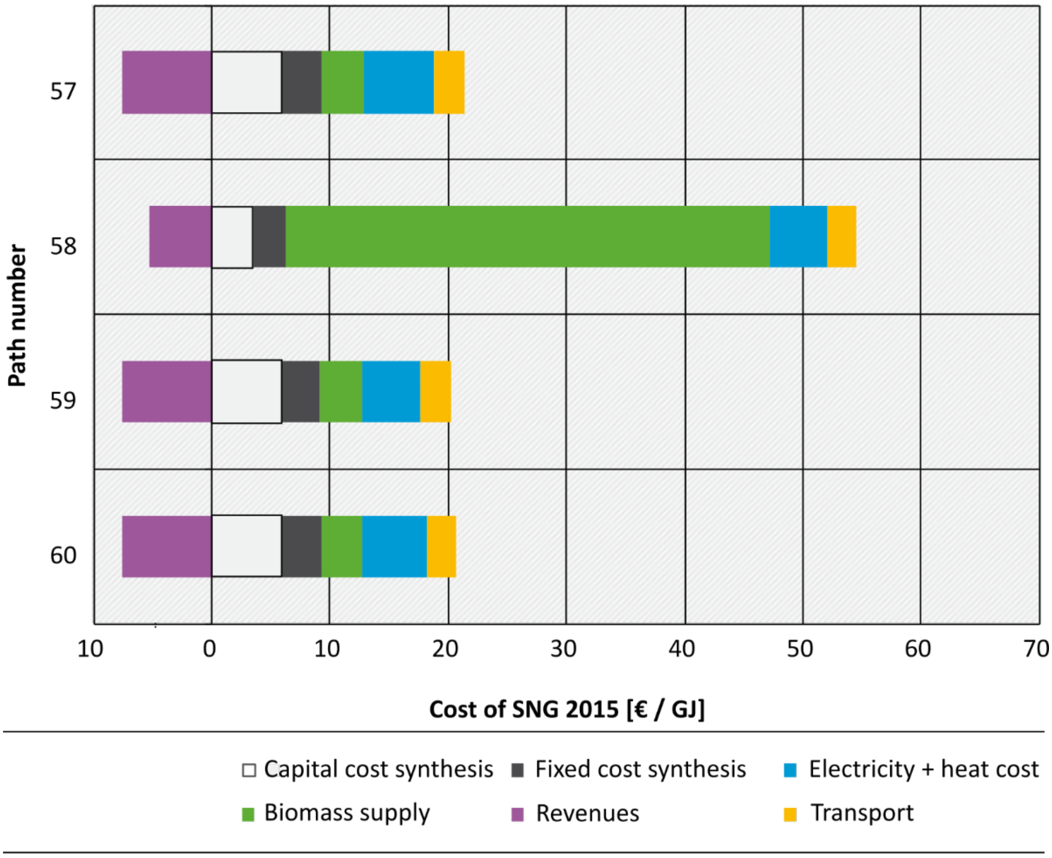
Source: Own representation, JOANNEUM RESEARCH

6.2.2.4 Biomethane

For conciseness, only the path numbers are given in the following results on the cost estimates for SNG supply paths.

Figure 94 shows the results of the cost estimation of the four biomethane paths for 2015 with the contributions of capital costs, fixed costs of the biogas plant and the biogas upgrading plant, biomass supply costs, electricity and heat costs, costs of transporting the product and revenues from the by-products. The cost differences are mainly due to the costs of biomass. In paths 57, 59 and 60 green waste and biowaste are used, in path 58 maize and manure. The costs of green waste and biowaste include the costs of collection and transport to the biogas plant, the biomass itself has no costs as a residual material. The capital costs for the biogas plant are twice as high for the biogas plant with green waste and biowaste as for maize (Billig 2016). The capital costs for biogas upgrading are in the range of 1,500 €/Nm^3/h for membrane separation and amine scrubbing and in the range of 1,700 €/Nm^3/h for pressurised water scrubbing and pressure swing absorption. In addition, the operation of the biogas plants as well as the biogas upgrading plants will incur costs for electricity (9 cent/kWh, industry electricity price) and heat (€9/GJ, from natural gas). The fermentation residues of the biogas plant can generate revenues as fertiliser. These revenues were estimated by means of the fertiliser value of the fermentation residue mass and the amount of fertiliser substituted. All four paths have higher costs (approx. by a factor of 1.5 to 6) than the fossil reference (approx. 8 €/GJ, based on approx. 3 cent/kWh industry natural gas price).

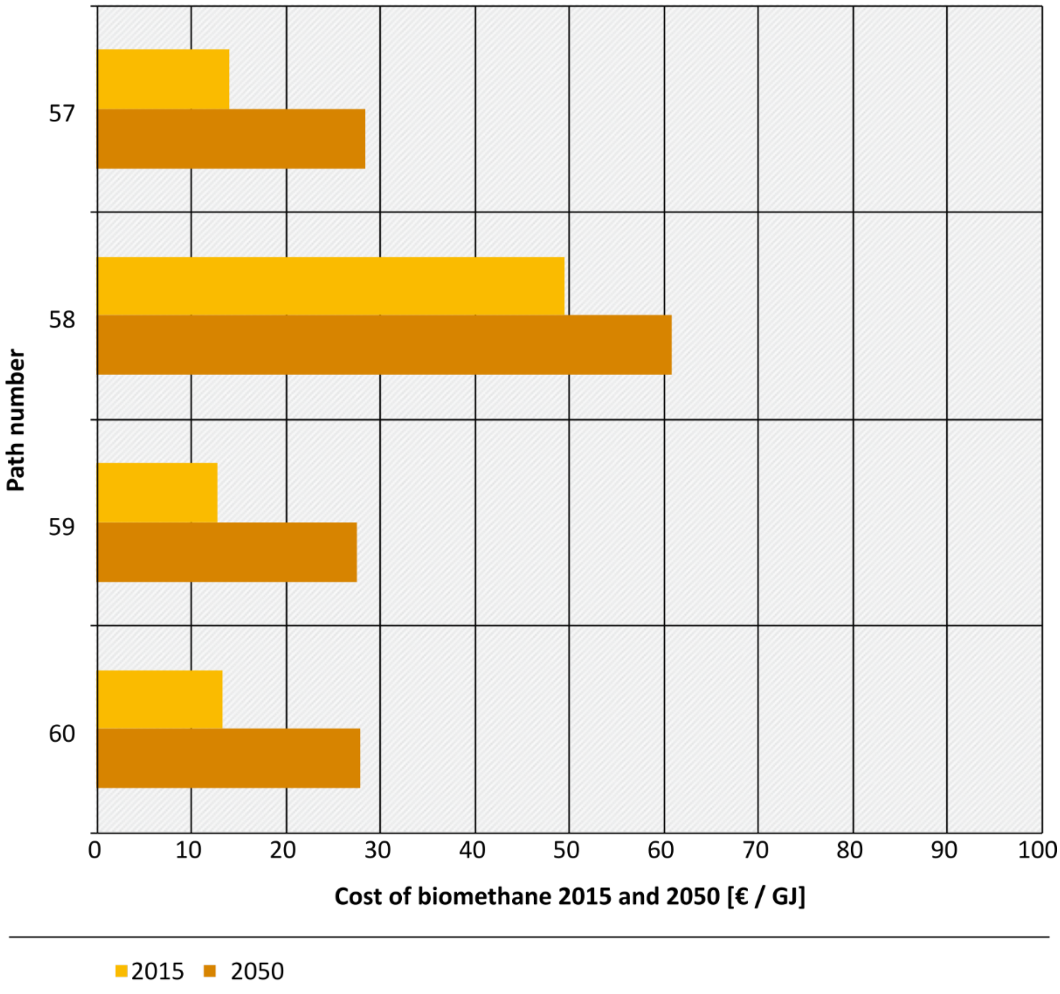
Figure 94: **Cost of biomethane 2015**



Source: Own representation, JOANNEUM RESEARCH

Figure 95 shows the results of the cost estimate of the four biomethane supply paths for 2015 and 2050. Compared to 2015, the costs in 2050 are higher, by 23% for path 58 and twice as high as in 2015 for paths 57, 59 and 60. The capital costs of the plants do not change in 2050 compared to 2015. This is due to the assumptions made for biomass costs in the reference year 2050. In path 58, the costs for maize increase by about 40% by 2050. For green waste and biowaste, the costs per organic dry matter were based on the costs for residual wood chips assumed for 2050. The capital costs of biogas plants do not change until 2050 due to the high degree of maturity in 2015.

Figure 95: Cost of biomethane in 2015 and 2050



Source: Own representation, JOANNEUM RESEARCH

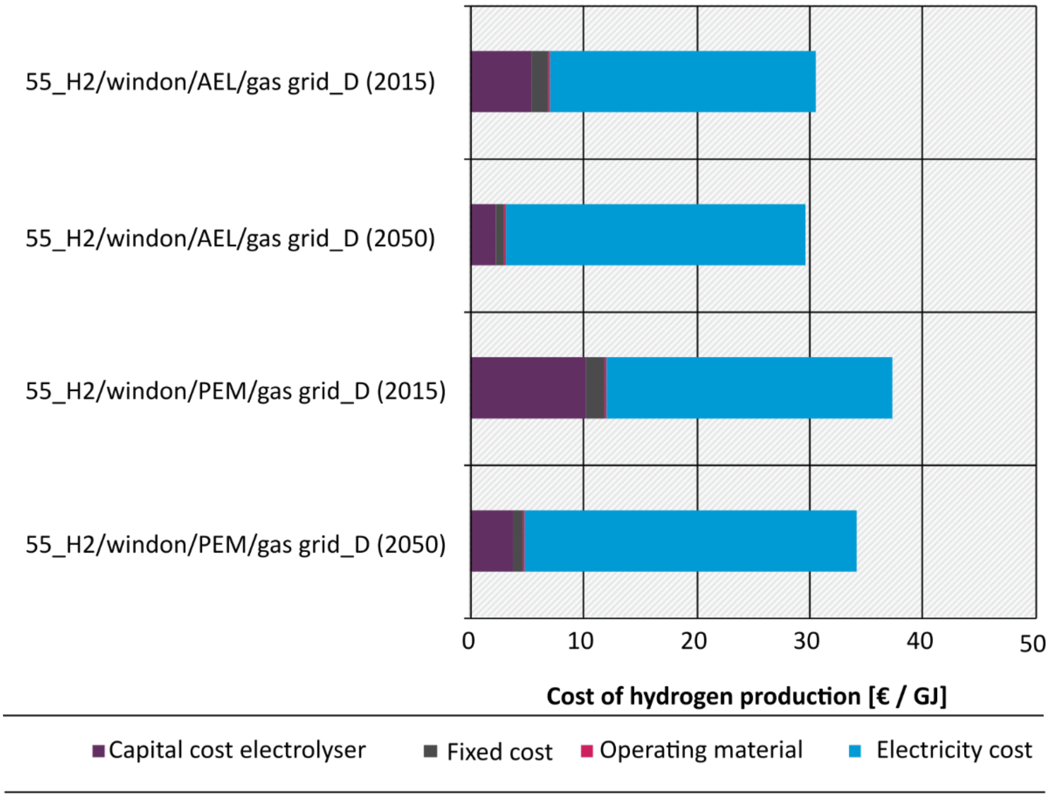
6.2.2.5 Hydrogen

In two supply paths, hydrogen is produced as a storable renewable energy carrier. The costs of hydrogen supply have already been examined in Chapter 6.2.1.2. Nevertheless the costs for paths 55 and 56 are described here again.

Figure 96 shows the specific hydrogen production costs in [€/GJ hydrogen] for the years 2015 and 2050 for the two supply paths (as described above under the assumption that the electrolysis is supplied from the associated power source for more than 8.000 full load hours anually, not including an electricity storage).

As Figure 96 shows, in 2015 and 2050 electricity costs will have by far the greatest influence on the costs of hydrogen supply in both paths. Due to the lower capital costs of alkaline electrolysis compared to PEM electrolysis, the costs in path 55 are slightly lower than in path 56. In the reference year 2050, path 55 has almost the same costs as in 2015, the lower capital costs are compensated due to increasing electricity transmission costs. In path 56, the costs in the reference year 2050 are slightly lower than in 2015 due to a stronger decrease in capital costs of PEM electrolysis.

Figure 96: Cost of hydrogen (paths 55 and 56) 2015 and 2050



Source: Own representaation, JOANNEUM RESEARCH

6.2.3 Conclusions cost estimates

This chapter summarises the results and the main factors influencing the cost of providing synthetic energy carriers based on renewable energy. Reference is also made to the corresponding results of the life cycle assessment.

In 52 of a total of 62 supply paths (PtL, PBtL, PtG) investigated, hydrogen is used with different power sources for electrolysis together with CO_2 from different sources for the synthesis of storable energy carriers. In eight paths (BtL, Bio-CH_4) biomass is converted into liquid or gaseous energy carriers without an external electricity or CO_2 source. In two paths hydrogen is produced by alkaline or PEM electrolysis.

For the electricity-based paths, the costs of electricity and, consequently, of hydrogen are the most important cost factor. The costs of energy-intensive CO_2 capture from air or, for the biomass-based paths, the costs of biomass are also strongly influencing the costs.

This cost analysis exclusively examines the technology related costs for plant construction and operation for the production of storable renewable energy carriers described above. Therefore it represents the relationships between technology values or future technology performance potentials and technology-related cost parameters. In particular, external environmental costs for climate damage caused by greenhouse gas emissions are not considered in this study.

- The type of renewable electricity source plays a crucial role in the cost of electricity-based supply paths.
  - Offshore wind power generation in Germany will have the highest costs in 2015 and 2050, followed by PV power in Germany and concentrated solar power (CSP) in Morocco. Electricity from geothermal energy in Iceland and from hydropower in Sweden

will have the lowest costs in 2015 and 2050. In the mid range are the costs of electricity from onshore wind power in Germany or Morocco and from PV at sites with high full load hours, in this study in Morocco and Saudi Arabia.

- Correspondingly, the supply paths with high electricity demand as well as electricity sources with high costs at rather unfavourable locations show the worst overall results. CO_2 capture from the air with direct air capture has a high electricity requirement, and in combination with the use of electricity from offshore wind power in Germany (e.g., paths 11 (FT), 33 (methanol), 49 (SNG)) have high product costs. In some paths, the high capital costs of high-temperature electrolysis (path 19 (FT)) or direct current transmission (HVDC) (path 5 (FT), path 27 (methanol), path 45 (SNG)) also contribute to the high costs of the supply paths.

- For remote sites not connected to the grid, 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, or storage facilities for hydrogen/CO_2 /electricity have to be used. Suche storage options have not been considered in this study. Using a sensitivity of the full-load hours, the costs were estimated for one path per product (path 4 (FT), path 26 (methanol), path 44 (SNG)), e.g., for PV electricity in Germany "isolated operation". This mode of operation leads to approx. 40% higher costs of the final energy carriers, since the capital costs from the construction of the plants over their lifetime are offset against a smaller quantity of produced fuels.

- Considering both the life cycle assessment and the cost estimates of renewable electricity generation as the main influencing factor in the electricity-based supply paths shows that PV electricity in Germany has both the highest global warming potential and comparatively high costs. On the other hand electricity from hydropower in Sweden has both the lowest global warming potential and comparatively very low costs. In the case of geothermal energy in Iceland, the lowest costs are offset by a comparatively high global warming potential, while the opposite is true for offshore wind power in Germany.

- The use of electricity from the grid mix in Germany (path 22 (FT), path 42 (methanol), path 54 (SNG)), which is particularly critical from the point of view of the life cycle assessment and the global warming potential, leads to comparatively low costs for 2015 as well as for 2050. It should be noted, though, that this result for the reference year 2015 does not take external environmental costs into account that result from the comparatively high fossil share in the German electricity mix. For the reference year 2050, however, external environmental costs play no significant role in the assumed transformation to a climate-neutral economy.

► When importing energy carriers from abroad, there are differences between electricity and liquid and gaseous energy carriers.

  - In the supply paths for liquid energy carriers, FT fuel and methanol, the cost estimates shows approx. 40% lower total costs with transport by tanker from Saudi Arabia (Path 6 (FT), Path 28 (methanol)) compared with electricity transmission to Germany by HVDC (Path 5 (FT), Path 27 (methanol)). In comparison to the LCA, in which the two transport variants have approximately the same global warming potential, the cost estimates show a clear difference.

  - For synthetic natural gas (SNG), three transport options were compared: SNG- transport by tanker or pipeline and electricity transmission with HVDC transmission (SNG -production in Germany). Pipeline transport has the lowest costs, closely followed by tanker transport. HVDC transmission has the highest costs (about 180% of pipeline costs). Compared to the LCA with the lowest global warming potential for electricity transmission by HVDC transmission, the results of the cost estimate also show a clear difference.

- Among the paths using biomass as a raw material, there are purely biomass-based paths (BtL, biomethane) and paths using biomass and electricity/hydrogen (PBtL).
  - In comparable paths in 2015 and 2050 (e.g., 1 and 8 - FT), the type of biomass (residues or cultivated biomass) does not lead to major differences in the costs of the supply paths.
  - PBtL syntheses with the same raw materials make better use of these, but - depending on the coupled power source - show significantly higher costs, as well as a significantly higher global warming potential in the life cycle assessment. This difference is smallest for 2015 and 2050 in paths 16 and 17 (FT) and 38 and 39 (methanol) at the Swedish site with biomass from forest residues or SRC pellets and electricity from hydropower.
  - The comparison between fully electricity-based paths (PtL) and biomass- and electricity-based paths (PBtL) with the same power source (e.g., Paths 9 and 10 (FT), 31 and 32 (methanol)) shows slightly higher costs for the biomass-based paths in 2050.
  - In 2050, biomethane paths based on biogenic residues will have comparable costs to those of synthetic natural gas (SNG). The exception is path 58, which uses maize and has the highest costs of all gaseous energy carriers.

A cross-product evaluation is only possible and useful to a limited extent, as already shown in the conclusion of the LCA. This is due to different uses, the fact that the use phase is not considered and a different number and diversification of the supply paths investigated. A comparison of the products purely in terms of calorific value tends to show that the production of hydrogen is associated with the lowest costs, followed by synthetic natural gas and biomethane, Fischer-Tropsch fuels and methanol. This ranking also reflects the increasing complexity of synthesis plants.

The informative value of the investigations carried out is limited in the same points as pointed out for the LCA and should be improved in subsequent studies.

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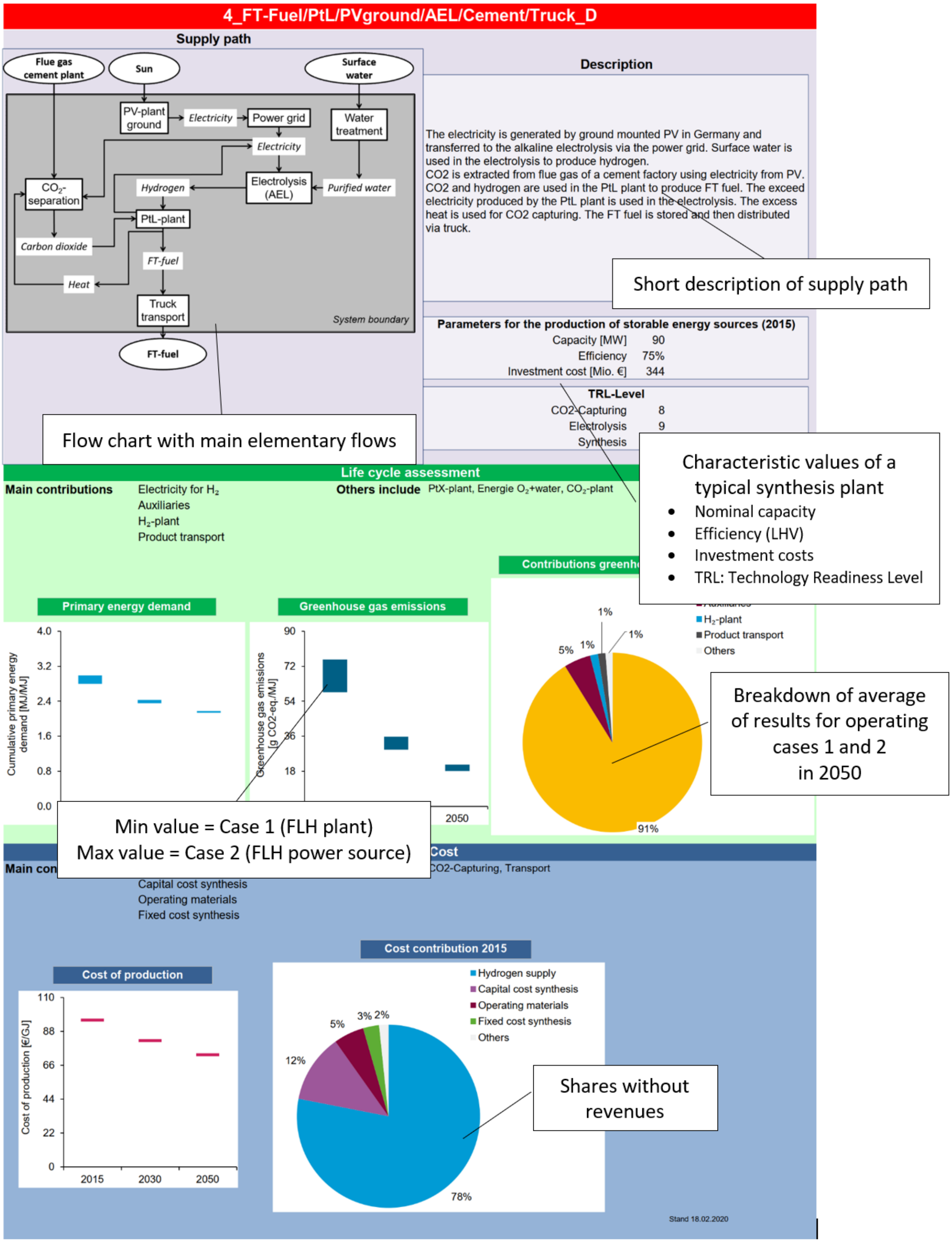
A Appendix: Fact sheets for all supply paths

Legend:



4_FT-Fuel/PtL/PVground/AEL/Cement/Truck_D

Supply path

Flow chart with main elementary flows

Description

The electricity is generated by ground mounted PV in Germany and transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is extracted from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity produced by the PtL plant is used in the electrolysis. The excess heat is used for CO2 capturing. The FT fuel is stored and then distributed via truck.

Short description of supply path

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	

Characteristic values of a typical synthesis plant

- Nominal capacity
- Efficiency (LHV)
- Investment costs
- TRL: Technology Readiness Level

Life cycle assessment

Main contributions Electricity for H_2
Auxiliaries
H_2-plant
Product transport

Others include PtX-plant, Energie O_2+water, CO_2-plant

Breakdown of average of results for operating cases 1 and 2 in 2050

Min value = Case 1 (FLH plant)
Max value = Case 2 (FLH power source)

Cost

Main con Capital cost synthesis
Operating materials
Fixed cost synthesis

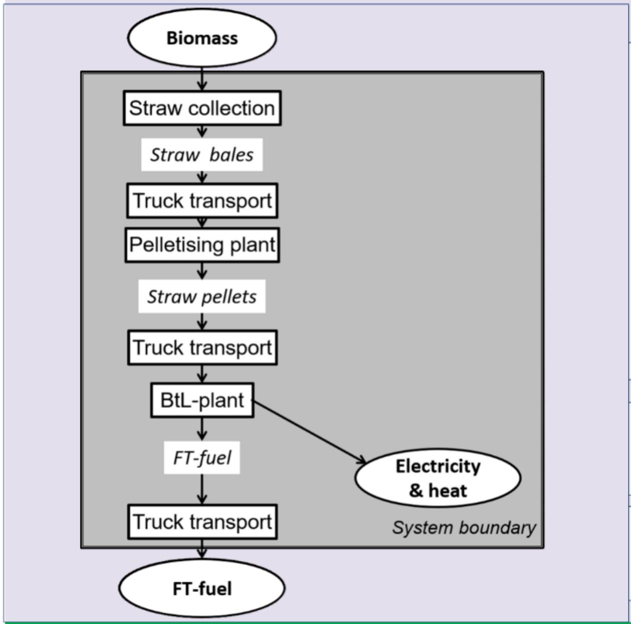
CO2-Capturing, Transport

Shares without revenues

Stand 18.02.2020

1_FT-Fuel/BtL/Straw/Truck_D

Supply path



Description

The straw from grain farming is collected in Germany and brought to the pelleting plant. The straw pellets are transported to the BtL plant. The biomass is gasified in the BtL plant and converted into FT fuel. Excess electricity and excess heat are used otherwise. The FT fuel is stored and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	37%
Investment cost [Mio. €]	533

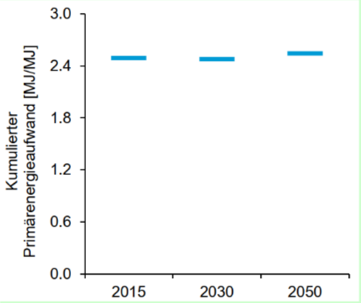
TRL-Level

CO_2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	8

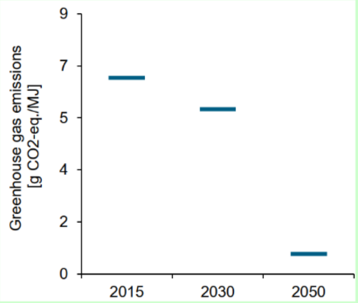
Life cycle assessment

Main contributions	Product transport Auxiliaries PtX-plant Biomass supply	**Others include**	none

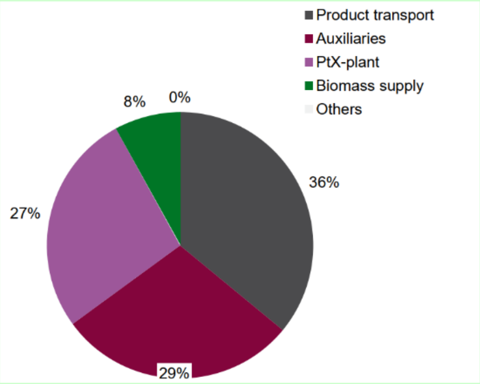
Primary energy demand



Greenhouse gas emissions



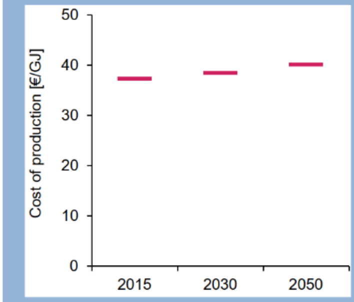
Contributions greenhouse gas emissions 2050



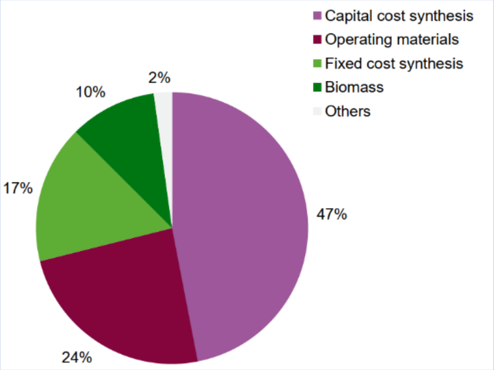
Estimated Cost

Main contributions	Capital cost synthesis Operating materials Fixed cost synthesis Biomass	**Others include**	Transport biomass, Transport

Cost of production



Cost contribution 2015



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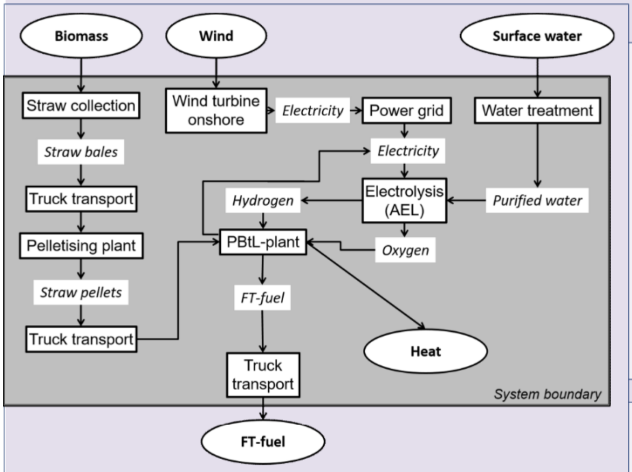
2_FT-Fuel/PBtL/WindON/Straw/AEL/Truck_D

Supply path



Description

The Electricity is generated by onshore wind power plants in Germany and is transferred to alkaline water electrolysis via the power grid. Surface water is used to produce hydrogen in the electrolysis. The oxygen output can also be used in the PBtL-plant. Residual straw from grain farming is collected and pelletised. CO2 is obtained from gasification of the straw pellets in the PBtL-plant. Both CO2 and hydrogen are used for FT-fuel production. Excess electricity is used in electrolysis. Excess heat from the BPtL-plant can be used otherwise. Produced FT-fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	62%
Investment cost [Mio. €]	729

TRL-Level

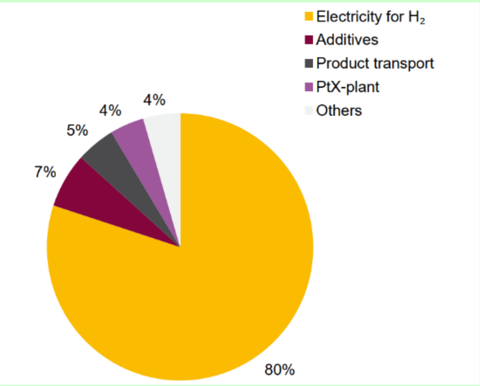
CO_2-Capturing	n.a.
Electrolysis	9
Synthesis	7

Life cycle assessment

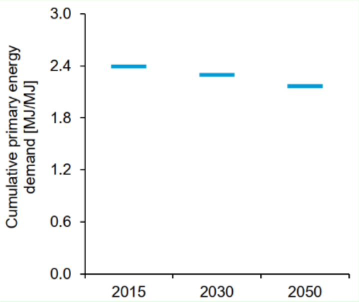
Main contributions
- Electricity for H_2
- Additives
- Product transport
- PtX plant

Others include H_2-plant, Energy O_2+H_2O, Biomass supply

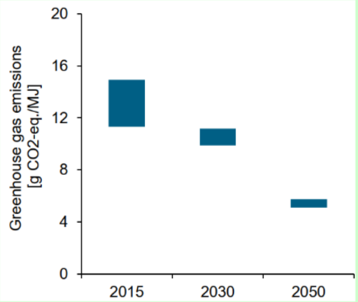
Contributions greenhouse gas emissions 2050



Primary energy demand



Greenhouse gas emissions



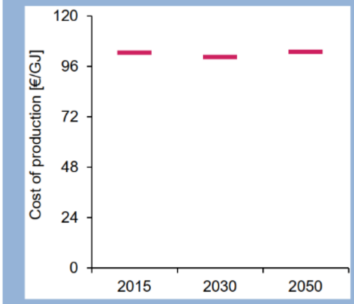
Estimated Cost

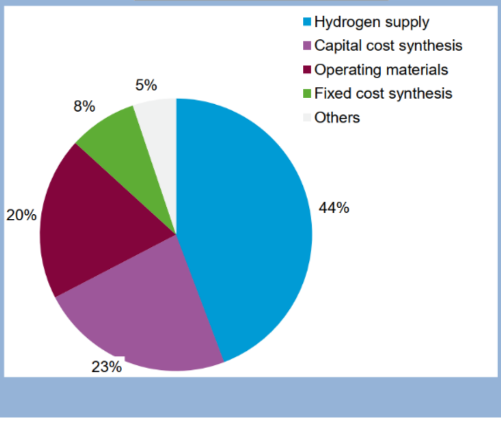
Main contributions
- Hydrogen supply
- Capital cost of synthesis
- Operating marterials
- Fixed cost of synthesis

Others include Biomass, Transport of biomass, Transport

Cost contribution 2015

Cost of production





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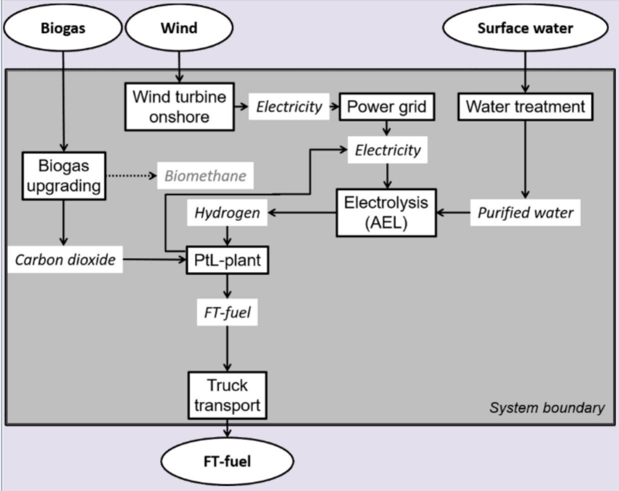
3_FT-Fuel/PtL/WindON/AEL/Biogas/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and transferred to the alkaline electrolysis via the power grid . Surface water is used to produce hydrogen in the electrolysis.
CO2 is obtained from an existing biogas upgrading facility. CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity from the PtL plant is used in electrolysis. The FT fuel is stored and is then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	9
Electrolysis	9
Synthesis	7

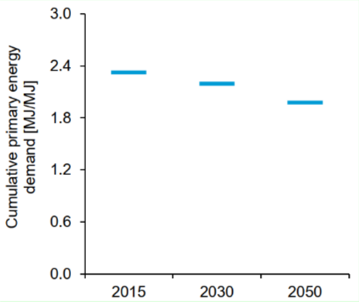
Life cycle assessment

Main contributions

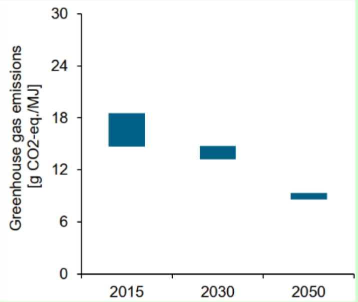
Electricity for H_2
CO_2-plant
Auxiliaries
H_2-plant

Others include Product transport, PtX-plant, Energie O_2+water

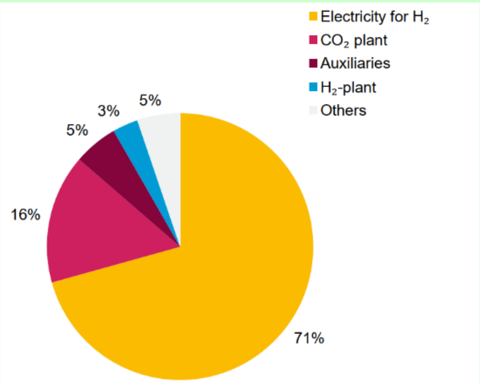
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



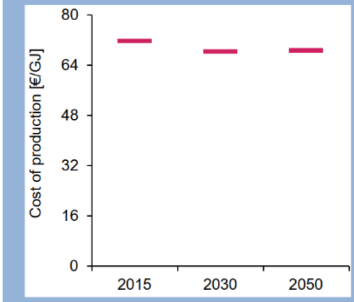
Estimated Cost

Main contributions

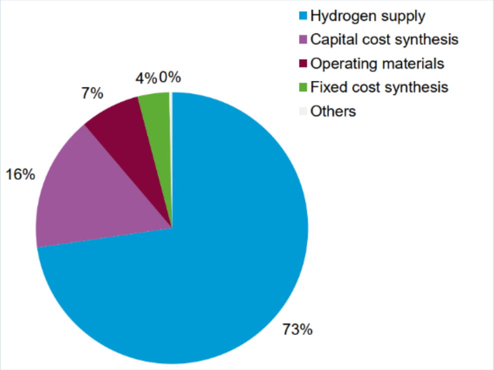
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include Transport

Cost of production



Cost contribution 2015



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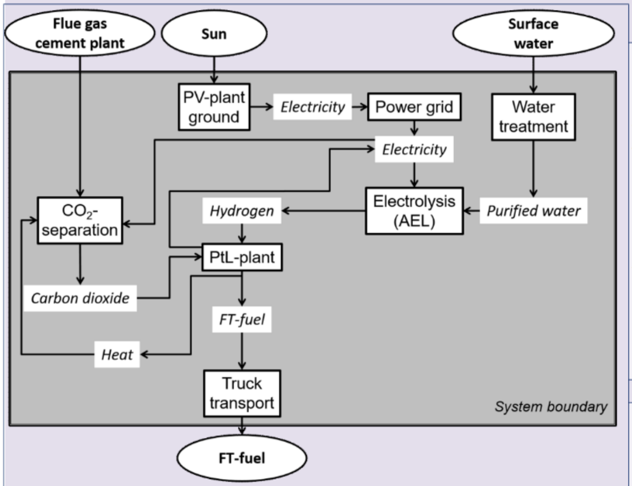
4_FT-Fuel/PtL/PVground/AEL/Cement/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is extracted from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity produced by the PtL plant is used in the electrolysis. The excess heat is used for CO2 capturing. The FT fuel is stored and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	7

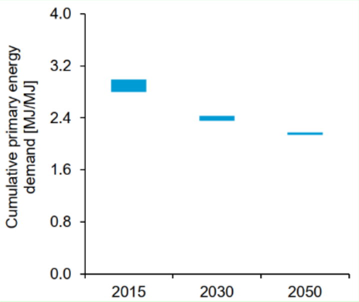
Life cycle assessment

Main contributions

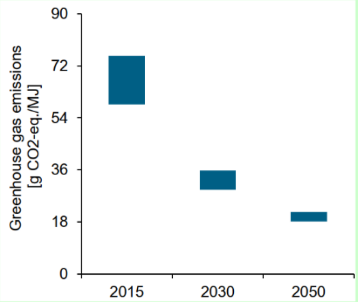
Electricity for H_2
Auxiliaries
H_2-plant
Product transport

Others include PtX-plant, Energie O_2+water, CO_2-plant

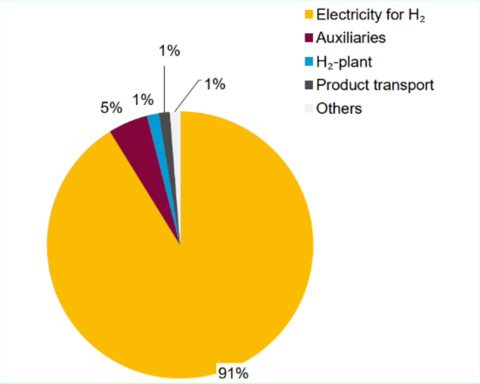
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



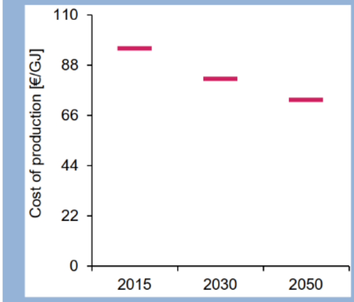
Estimated Cost

Main contributions

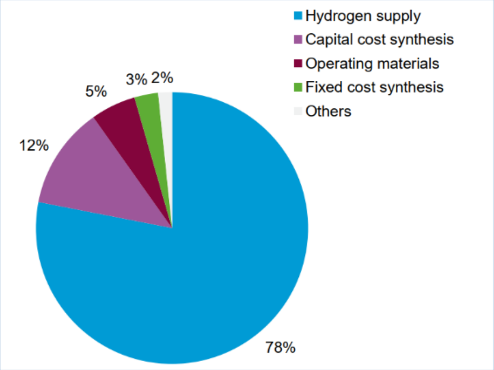
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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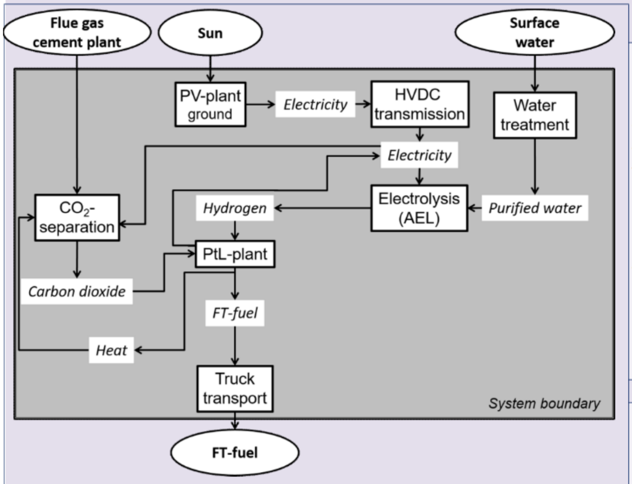
5_FT-Fuel/PtL/PVground/AEL/Cement/HVDC+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and transferred to Germany for alkaline electrolysis via the HVDC grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is extracted from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity produced by the PtL plant is used in electrolysis. The exceed heat is used for CO2 capturing. The FT fuel is stored and then distributed via a truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

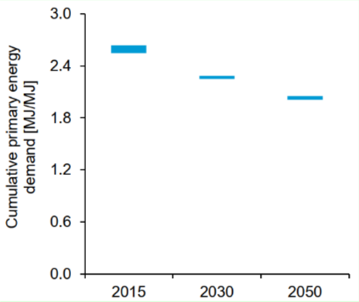
CO2-Capturing	8
Electrolysis	9
Synthesis	7

Life cycle assessment

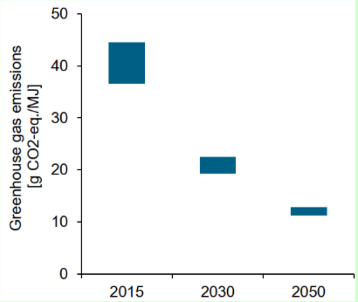
Main contributions
Electricity for H_2
Auxiliaries
Stromtransport HVDC
Product transport

Others include H_2-plant, PtX-plant, Energie O_2+water, CO_2-plant

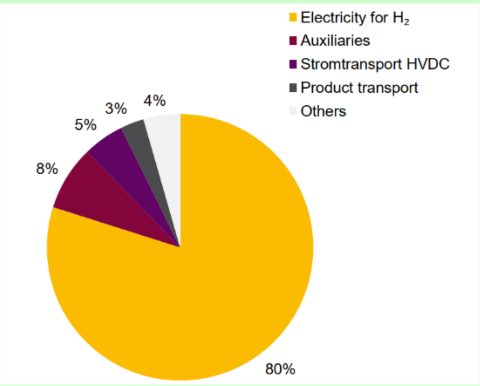
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

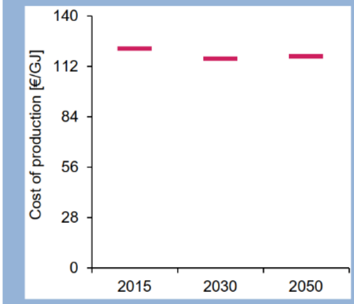


Estimated Cost

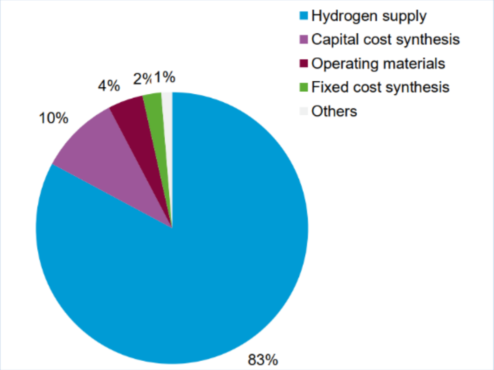
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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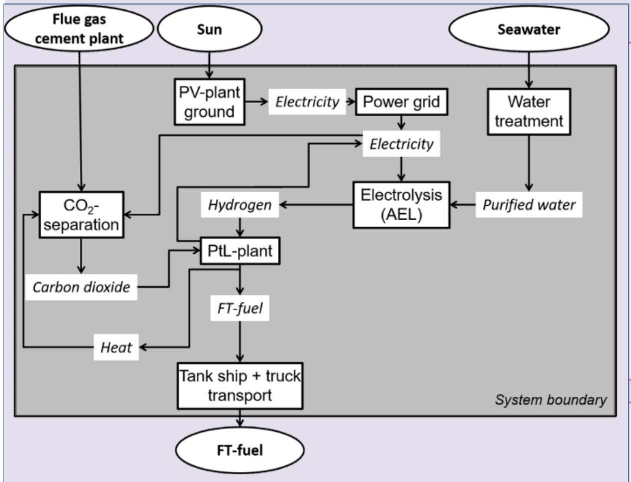
6_FT-Fuel/PtL/PVground/AEL/Cement/Tanker+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and transferred to alkaline electrolysis via the power grid. Seawater is used in electrolysis to produce hydrogen.
CO2 is extracted from the flue gas of a cement factory using electricity from PV.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity generated by the PtL plant is used in the electrolysis. The FT fuel is stored, then transported to Germany via ship and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

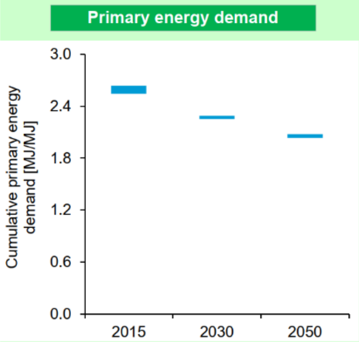
CO2-Capturing	8
Electrolysis	9
Synthesis	7

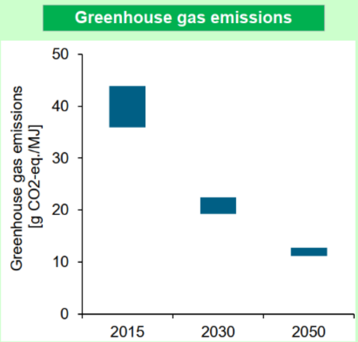
Life cycle assessment

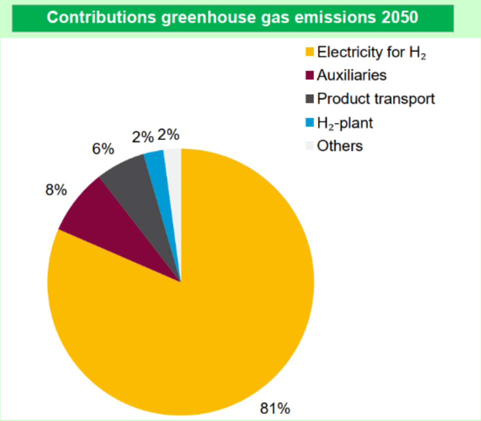
Main contributions

- Electricity for H_2
- Auxiliaries
- Product transport
- H_2-plant

Others include PtX-plant, Energie O_2+water, CO_2-plant





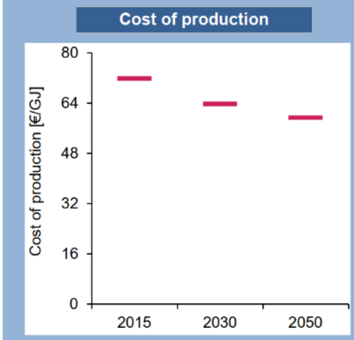


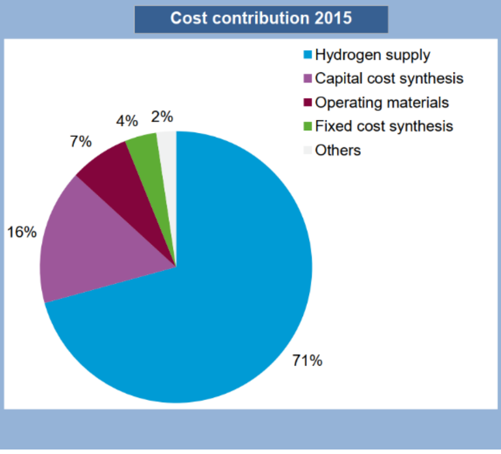
Estimated Cost

Main contributions

- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include CO2-Capturing, Transport





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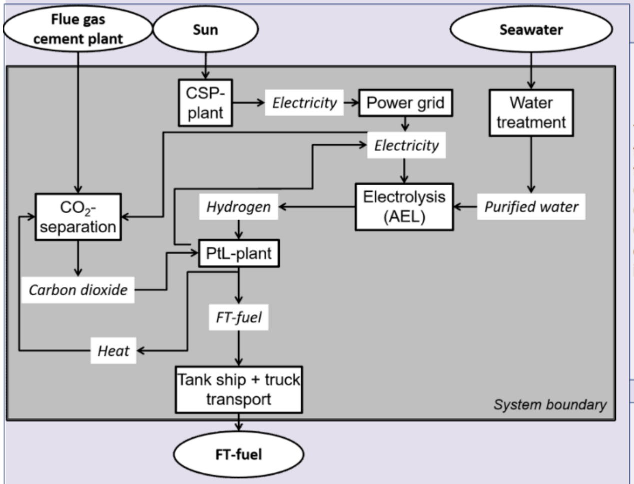
7_FT-Fuel/PtL/CSP/AEL/Cement/Tanker+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by a CSP power plant in Saudi Arabia and transferred to alkaline electrolysis via the power grid. Sea water is used in the electrolysis to produce hydrogen.
CO2 is extracted from flue gas of a cement factory using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity generated by the PtL plant is used in the electrolysis. The FT fuel is stored, then transported to Germany via ship and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

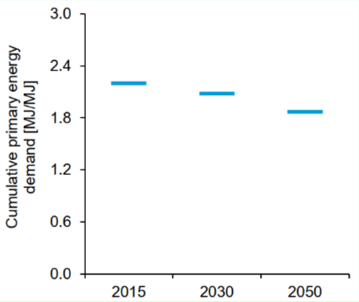
CO2-Capturing	8
Electrolysis	9
Synthesis	7

Life cycle assessment

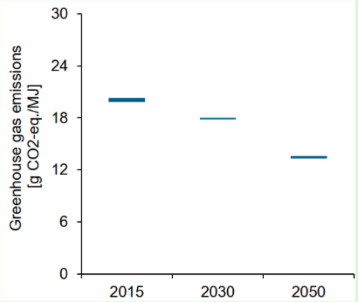
Main contributions
Electricity for H_2
Auxiliaries
Product transport
H_2-plant

Others include PtX-plant, Energie O_2+water, CO_2-plant

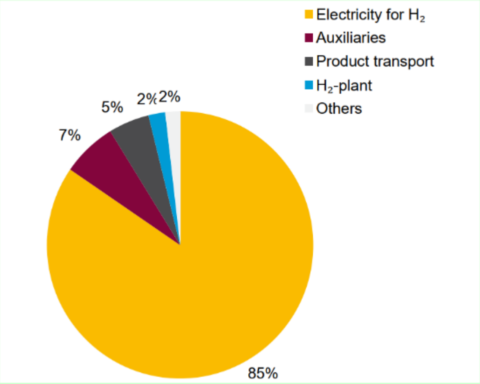
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

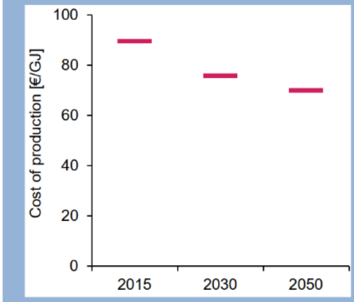


Estimated Cost

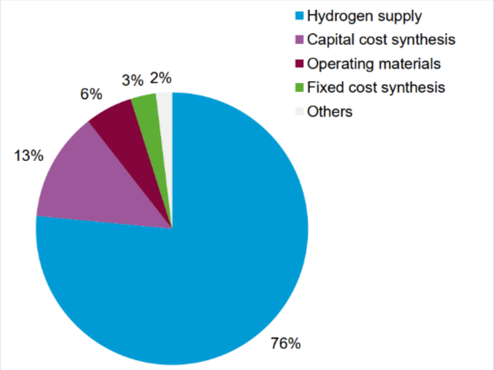
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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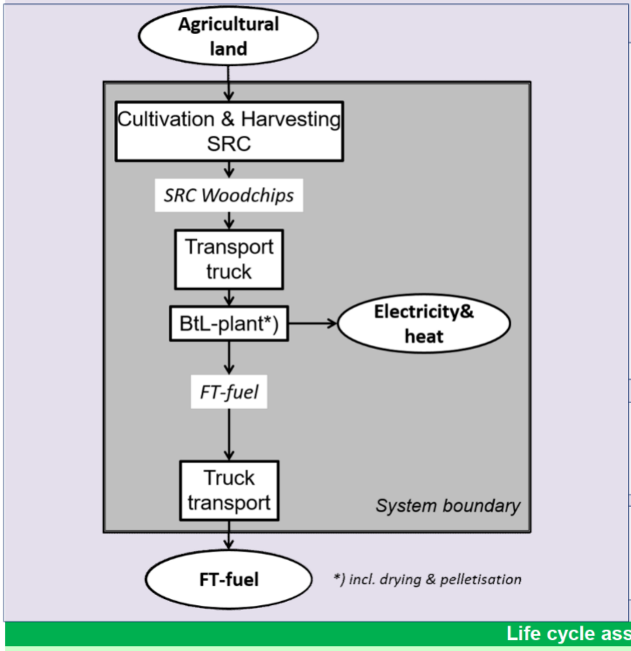
8_FT-Fuel/BtL/SRC Pellets/Truck_D

Supply path



Description

Wood from a short rotation plantation is used for the production of wood chips in Germany. The wood chips are transported to the PtL plant via truck. After drying and pelletising, the wood chips are gasified in the BtL plant and converted into FT fuel. The exceed electricity and exceed heat are used otherwise. The FT fuel is stored and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	37%
Investment cost [Mio. €]	533

TRL-Level

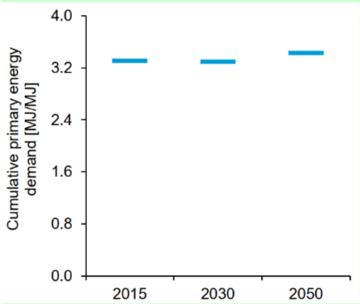
CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	8

Life cycle assessment

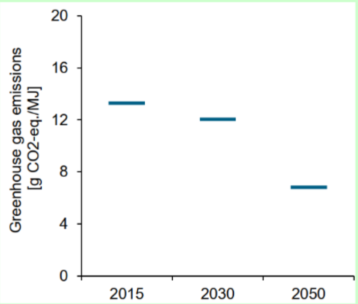
Main contributions
- Biomass supply
- Product transport
- Auxiliaries
- PtX-plant

Others include none

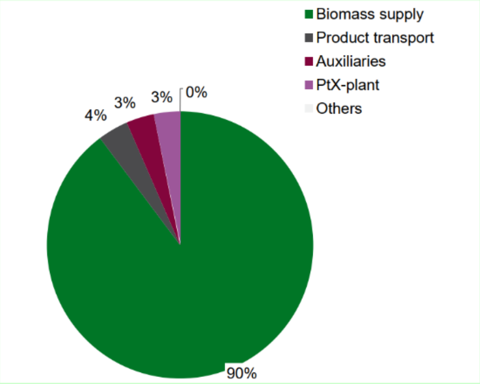
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

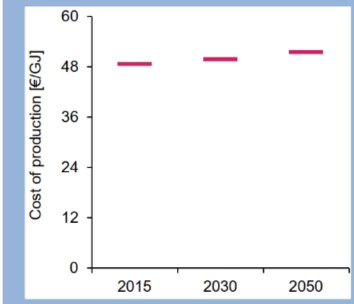


Estimated Cost

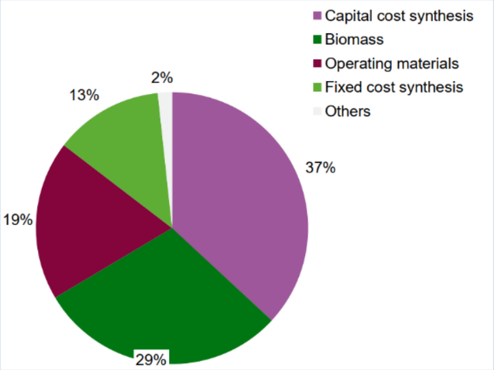
Main contributions
- Capital cost synthesis
- Biomass
- Operating materials
- Fixed cost synthesis

Others include Transport biomass, Transport

Cost of production



Cost contribution 2015



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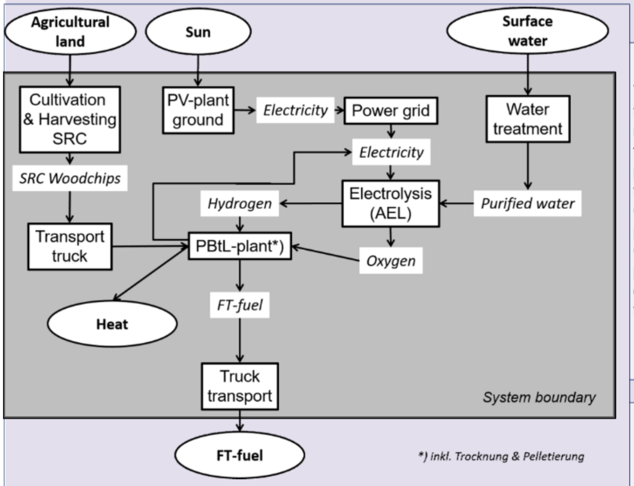
9_FT-Fuel/PBtL/PVground/SRC Pellets/AEL/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. The generated oxygen is used for gasification. Wood from a short rotation plantation is used for the production of wood chips in Germany. The wood chips are transported to the PBtL plant via truck.
CO2 is obtained from the gasification of pellets from short-rotation plantations in the BPtL plant.
CO2 from the gasification and hydrogen are used in the PBtL plant to produce FT fuel. The exceed electricity from the PBtL plant is used in the electrolysis, the exceed heat is used otherwise. The FT fuel is stored and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	62%
Investment cost [Mio. €]	729

TRL-Level

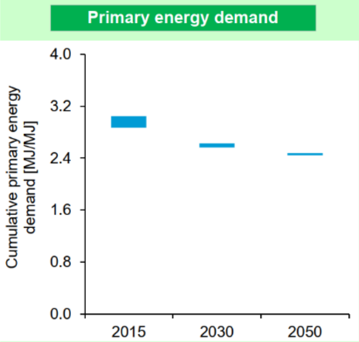
CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

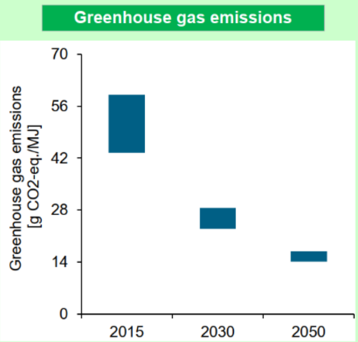
Life cycle assessment

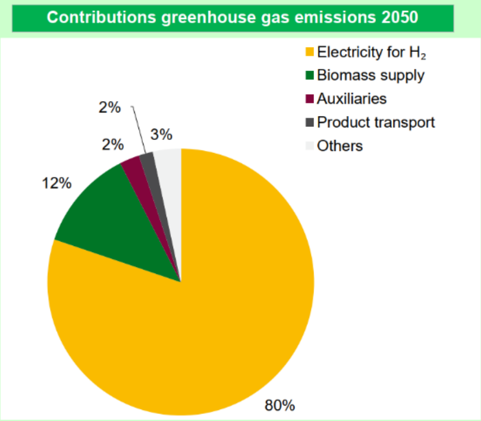
Main contributions

- Electricity for H_2
- Biomass supply
- Auxiliaries
- Product transport

Others include PtX-plant, H_2-plant, Energie O_2+water


Primary energy demand


Greenhouse gas emissions

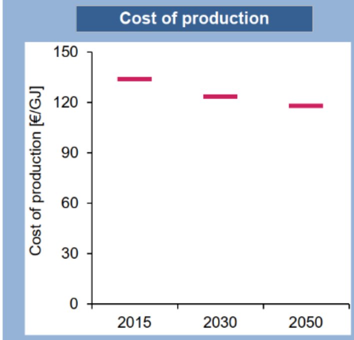

Contributions greenhouse gas emissions 2050

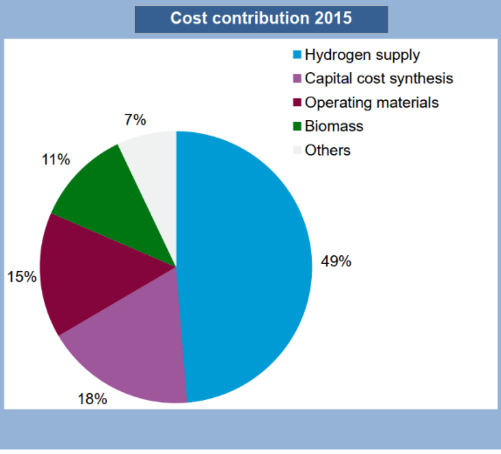
Estimated Cost

Main contributions

- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Biomass

Others include Fixed cost synthesis, Transport biomass, Transport


Cost of production


Cost contribution 2015

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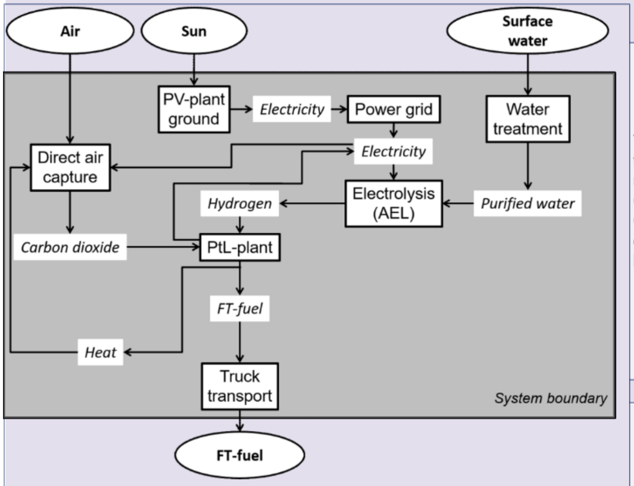
10_FT-Fuel/PtL/PVground/AEL/DAC/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is extracted from the air (DAC) using electricity from PV.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity generated by the PtL plant is used in the electrolysis, the exceed heat is used in the DAC. The FT fuel is stored and then distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

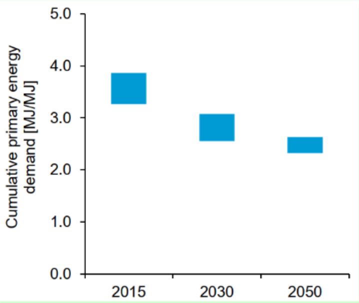
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

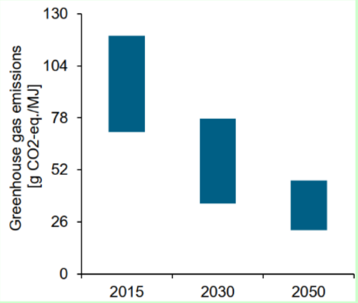
Main contributions
Electricity for H_2
CO_2-plant
Energy for CO_2
Auxiliaries

Others include H_2-plant, Product transport, PtX-plant, Energie O_2+water

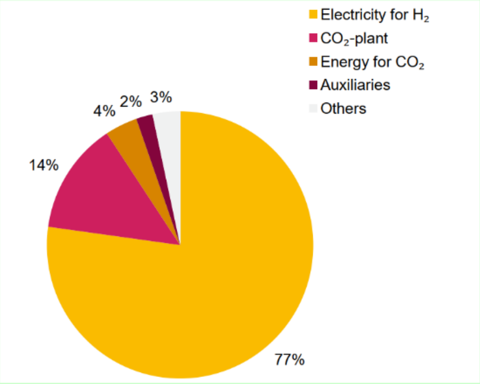
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

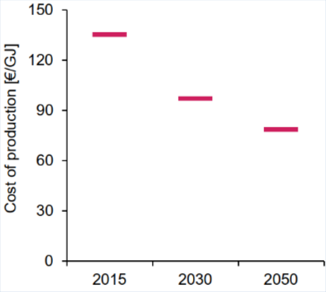


Estimated Cost

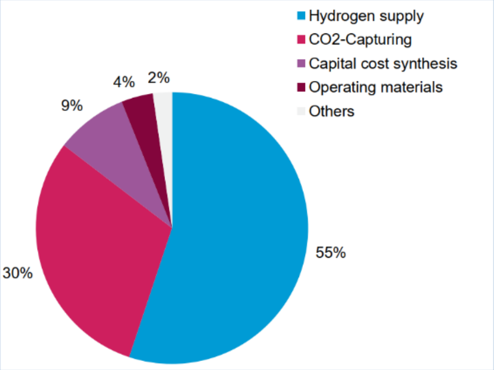
Main contributions
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Operating materials

Others include Fixed cost synthesis, Transport

Cost of production



Cost contribution 2015



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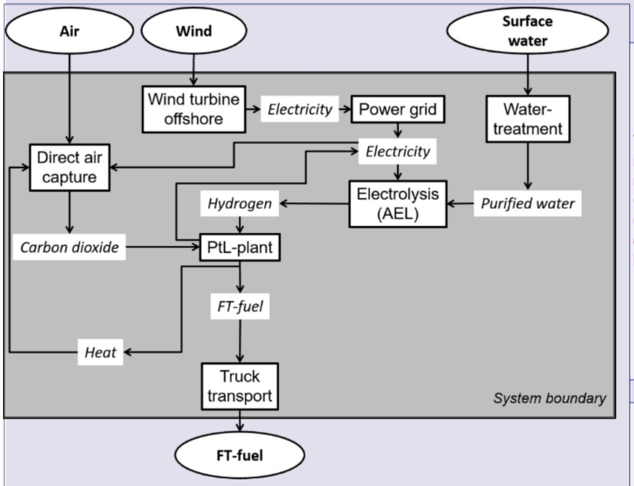
11_FT-Fuel/PtL/WindOFF/AEL/DAC/Truck_D

Supply path



Description

The electricity is generated by offshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is extracted from the air (DAC) using electricity from wind.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The exceed electricity produced by the PtL plant is used for the electrolysis. The exceed heat for the DAC. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

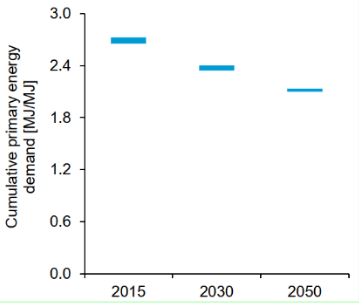
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

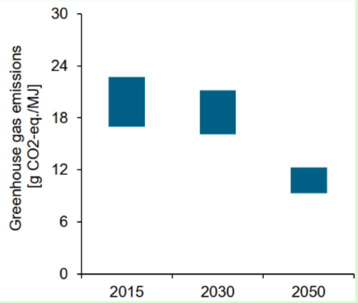
Main contributions
Electricity for H_2
CO_2-plant
Auxiliaries
H_2-plant

Others include Energy for CO_2, Product transport, PtX-plant, Energie O_2+water

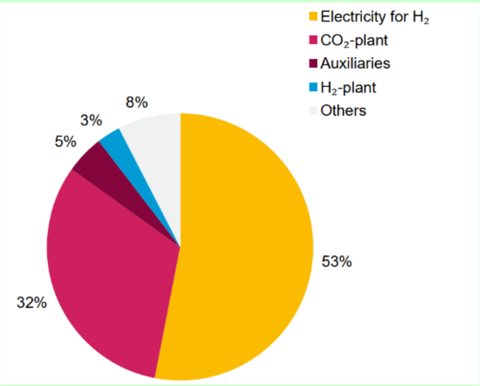
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

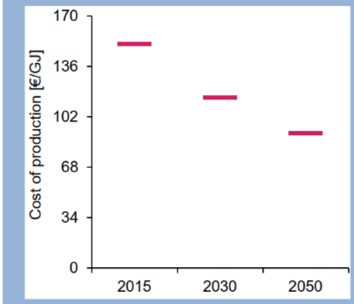


Estimated Cost

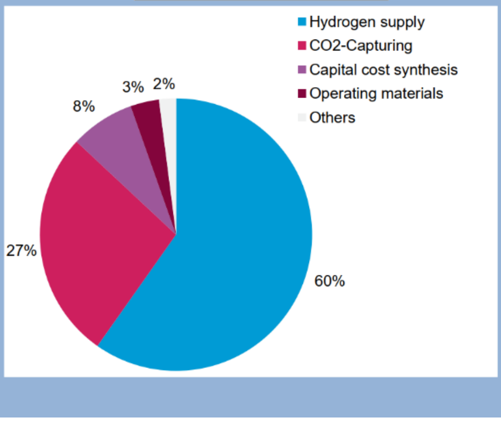
Main contributions
Hydrogen supply
CO2-capturing
Capital cost synthesis
Operating materials

Others include Fixed cost synthesis, Transport

Cost of production



Cost contribution 2015



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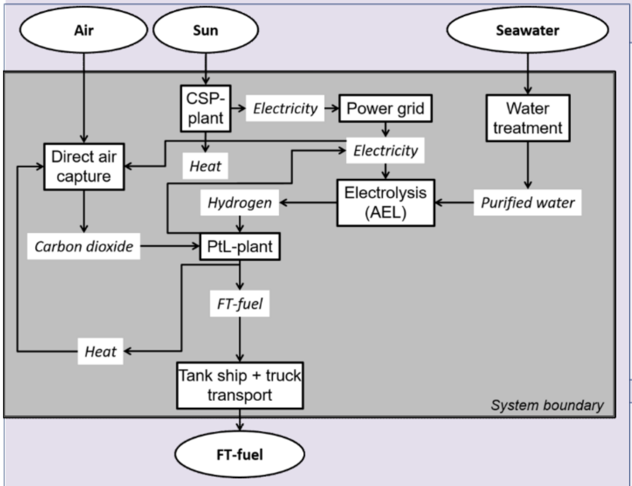
12_FT-Fuel/PtL/CSP/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by a CSP power plant in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is extracted from the air (DAC) using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The excess electricity from the PtL plant is used for the electrolysis. The excess heat is used for the DAC. The FT fuel is stored, then transported to Germany via ship and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

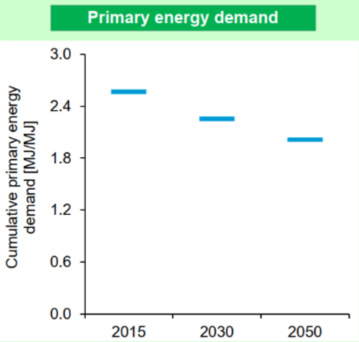
TRL-Level

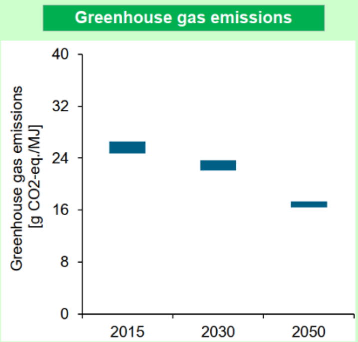
CO2-Capturing	7
Electrolysis	9
Synthesis	7

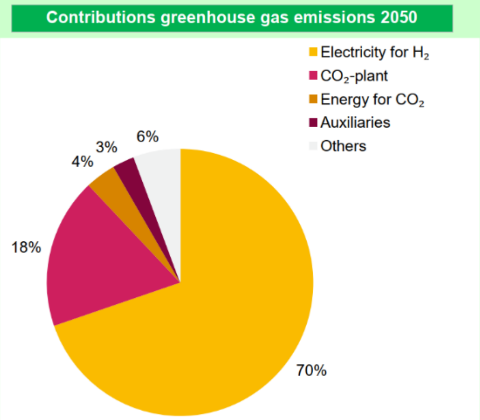
Life cycle assessment

Main contributions
Electricity for H_2
CO_2-plant
Energy for CO_2
Auxiliaries

Others include Product transport, H_2-plant, PtX-plant, Energie O_2+water


Primary energy demand

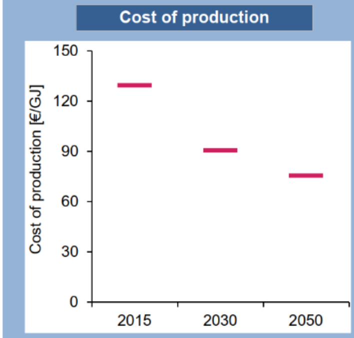

Greenhouse gas emissions

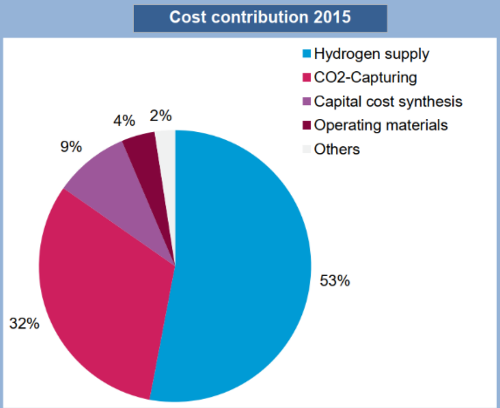

Contributions greenhouse gas emissions 2050

Estimated Cost

Main contributions
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Operating materials

Others include Fixed cost synthesis, Transport


Cost of production


Cost contribution 2015

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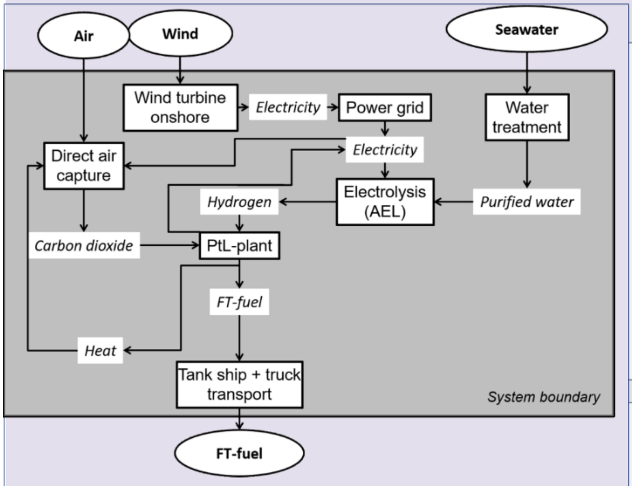
13_FT-Fuel/PtL/WindON/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by onshore wind power plants in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is extracted from the air (DAC) using electricity from wind power. CO2 and hydrogen are used in the PtL plant to produce FT fuel. The excess electricity from the PtL plant is used for the electrolysis. The excess heat is used for the DAC. The FT fuel is stored, then transported to Germany via ship and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

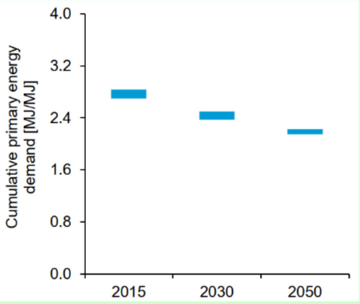
Life cycle assessment

Main contributions
Electricity for H_2
CO_2-plant
Auxiliaries
Product transport

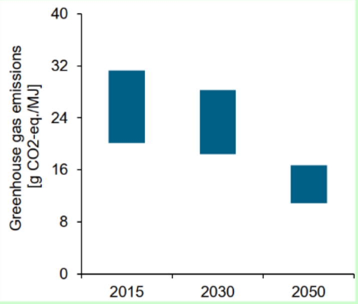
Others include Energy for CO_2, H_2-plant, PtX-plant, Energie O_2+water

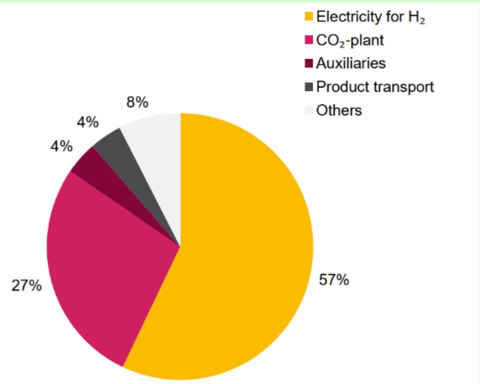
Contributions greenhouse gas emissions 2050

Primary energy demand



Greenhouse gas emissions





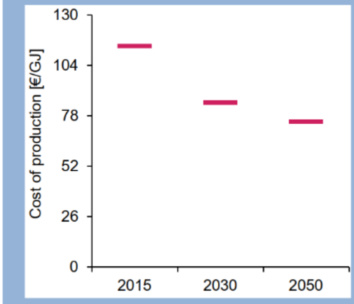
Estimated Cost

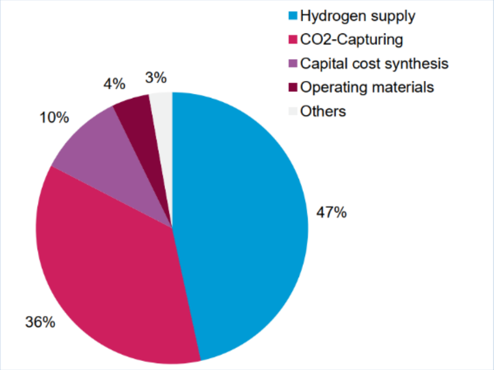
Main contributions
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Operating materials

Others include Fixed cost synthesis, Transport

Cost contribution 2015

Cost of production





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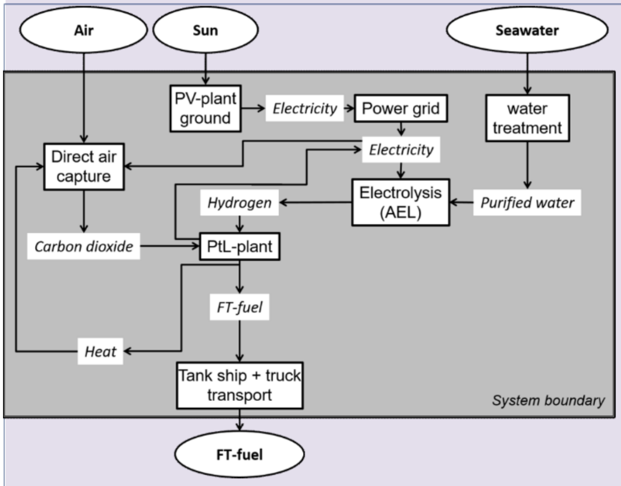
14_FT-Fuel/PtL/PVground/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by ground mounted PV in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is extracted from the air (DAC) using electricity from PV.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity from the PtL plant is used for the electrolysis. Excess heat is used for the DAC. The FT fuel is stored, then transported to Germany via ship and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

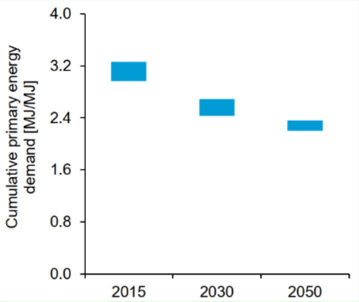
Life cycle assessment

Main contributions

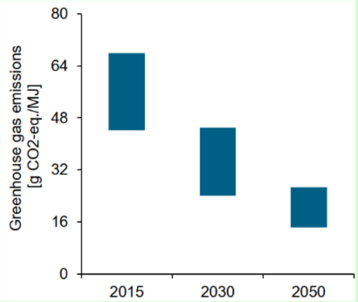
Electricity for H_2
CO_2-plant
Energy for CO_2
Auxiliaries

Others include Product transport, H_2-plant, PtX-plant, Energie O_2+water

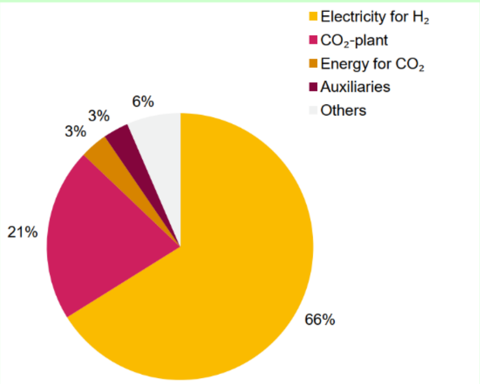
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



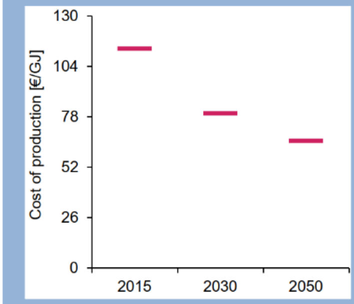
Estimated Cost

Main contributions

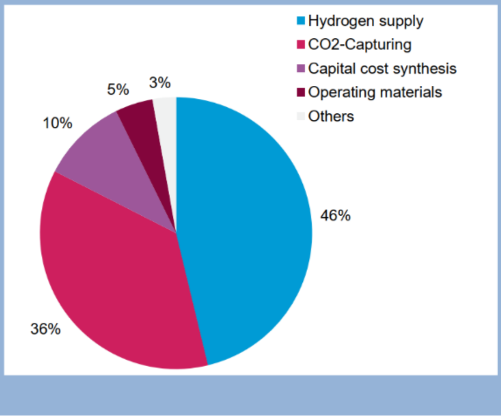
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Operating materials

Others include Fixed cost synthesis, Transport

Cost of production



Cost contribution 2015



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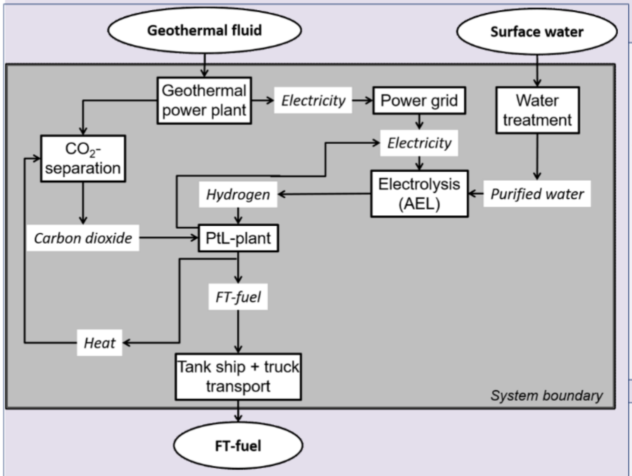
15_FT-Fuel/PtL/Geothermal/AEL/Geothermal/Tanker+Truck_Iceland

Supply path



Description

The electricity will be generated in a geothermal power plant in Iceland and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is extracted from the geothermal fluid using heat and electricity from geothermal energy.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. The FT fuel is stored, then brought to Germany via a tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

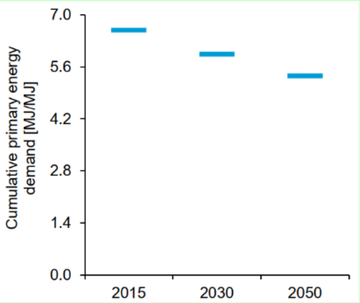
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

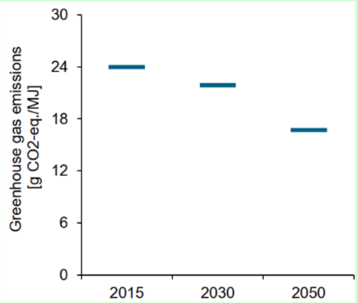
Main contributions
- Electricity for H_2
- CO_2-plant
- Energy for CO_2
- Auxiliaries

Others include Product transport, H_2-plant, PtX-plant, Energie O_2+water

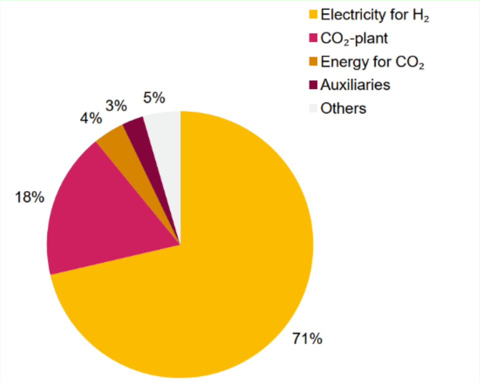
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

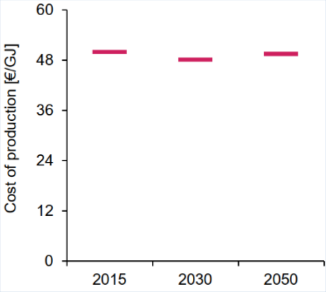


Estimated Cost

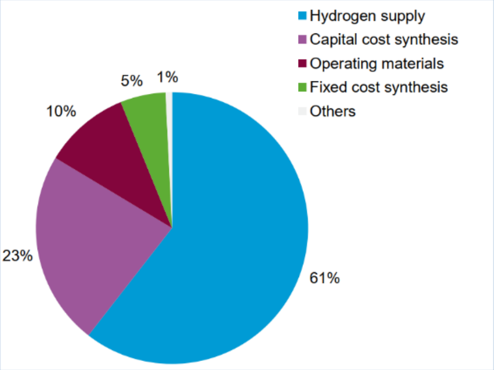
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include Transport

Cost of production



Cost contribution 2015



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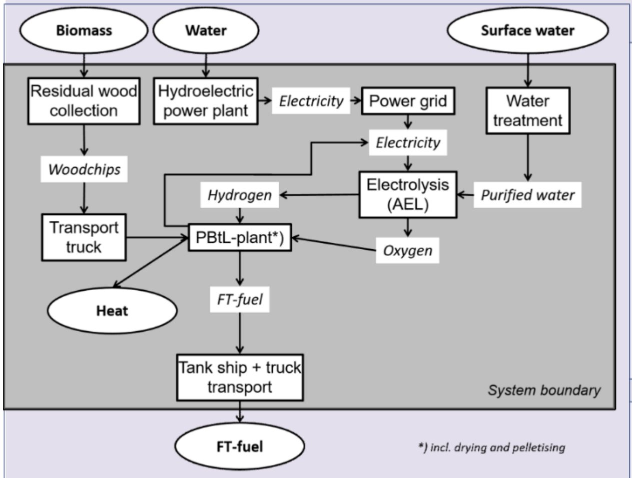
16_FT-Fuel/PBtL/Hydro/Residual Forrest Wood /AEL/Tanker+Truck_Sweden

Supply path



Description

The electricity is generated by hydroelectric power plants in Sweden and transferred to alkaline electrolysis via the electricity grid. Surface water is used in the electrolysis to produce hydrogen. The oxygen output can also be used in the PBtL plant. The residual forest wood is collected and transported to the PBtL plant.
CO2 is obtained from the gasification of residual forest wood in the BPtL plant.
CO2 from the gasification and hydrogen are used in the PBtL plant to produce FT fuel. The excess electricity from the PBtL plant is used in the electrolysis. The FT fuel is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	62%
Investment cost [Mio. €]	729

TRL-Level

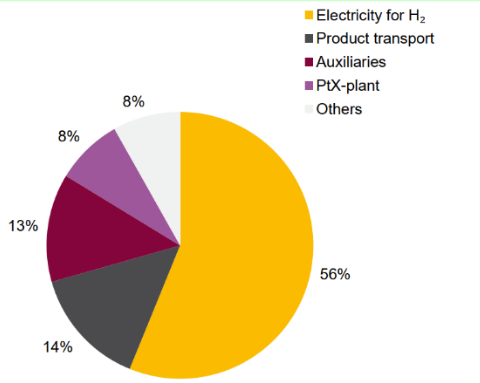
CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

Life cycle assessment

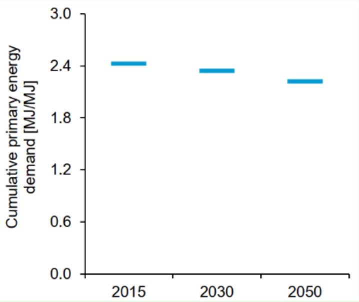
Main contributions
- Electricity for H_2
- Product transport
- Auxiliaries
- PtX-plant

Others include H_2-plant, Biomass supply, Energie O_2+water

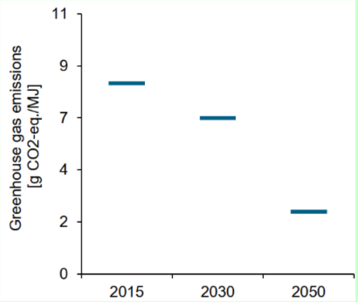
Contributions greenhouse gas emissions 2050



Primary energy demand



Greenhouse gas emissions

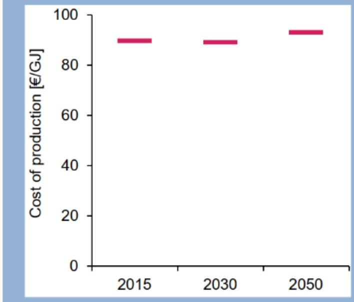


Estimated Cost

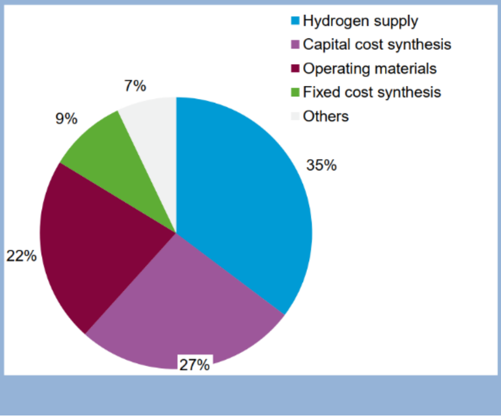
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include Biomass, Transport biomass, Transport

Cost of production



Cost contribution 2015



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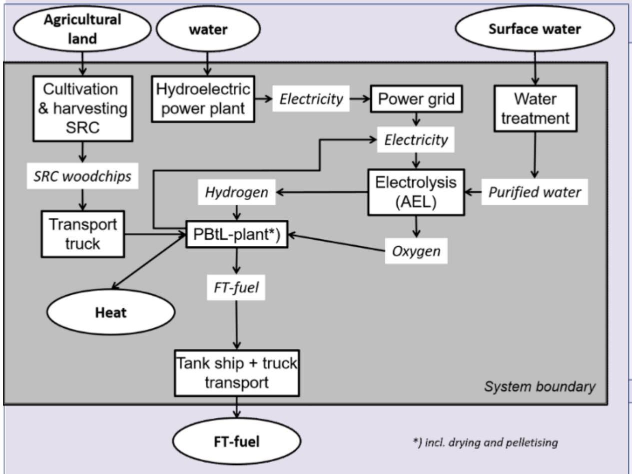
17_FT-Fuel/PBtL/Hydro/SRC Pellets/AEL/Tanker+Truck_Sweden

Supply path



Description

The electricity is generated by hydroelectric power plants in Sweden and transferred to alkaline electrolysis via the electricity grid. Surface water is used in the electrolysis to produce hydrogen. The oxygen output can also be used in the PBtL plant. Wood from a short rotation plantation is used to produce wood chips in Sweden. Those are transported to the PBtL plant by truck.
CO2 is obtained from the gasification of pellets from short rotation plantations in the BPtL plant.
CO2 from the gasification and hydrogen are used in the PBtL plant to produce FT fuel. Excess electricity from the PBtL plant is used for electrolysis. Excess heat is used otherwise. The FT fuel is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	62%
Investment cost [Mio. €]	729

TRL-Level

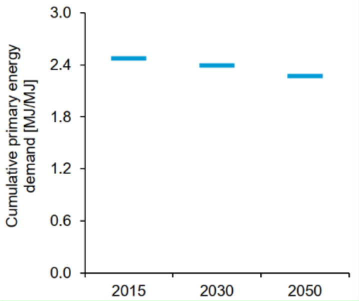
CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

Life cycle assessment

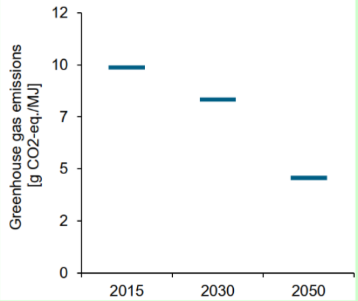
Main contributions
Biomass supply
Electricity for H_2
Product transport
Auxiliaries

Others include PtX-plant, H_2-plant, Energie O_2+water

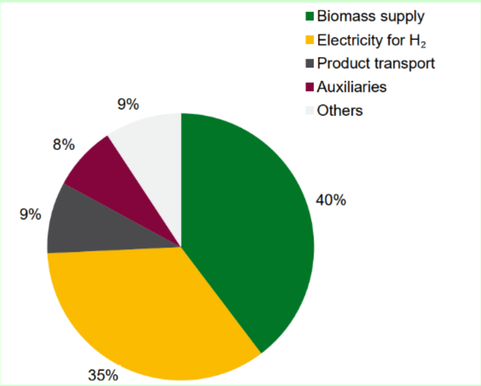
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

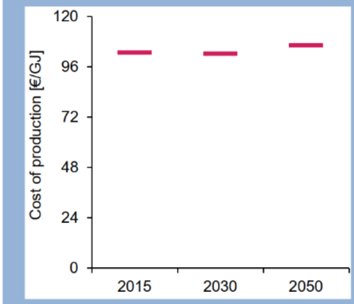


Estimated Cost

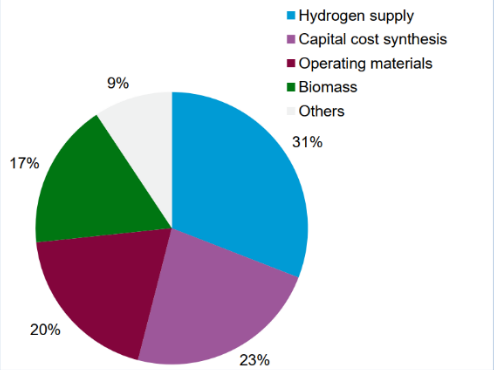
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Biomass

Others include Fixed cost synthesis, Transport biomass, Transport

Cost of production



Cost contribution 2015



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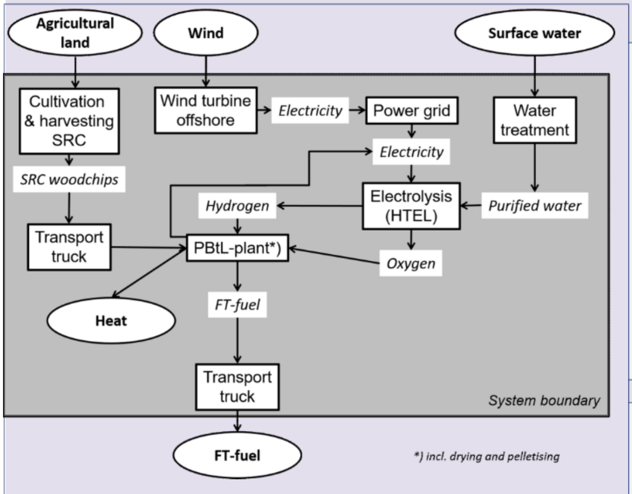
18_FT-Fuel/PBtL/WindOFF/SRC Pellets/HTEL/Truck_D

Supply path



*) incl. drying and pelletising

Description

The electricity is generated by offshore wind power plants in Germany and transported to the high-temperature electrolysis plant via the power grid. Surface water is used in the electrolysis to produce hydrogen. The oxygen output can also be used in the PBtL plant. Wood from a short rotation plantation is used to produce wood chips in Germany. It is transported to the PBtL plant by truck.
CO2 is obtained from the gasification of pellets from short-rotation plantations in the PBtL plant.
CO2 and hydrogen are used in the PBtL plant to produce FT fuel. Excess electricity from the PBtL plant is used in electrolysis. Excess heat can be used otherwise. The FT-fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	62%
Investment cost [Mio. €]	729

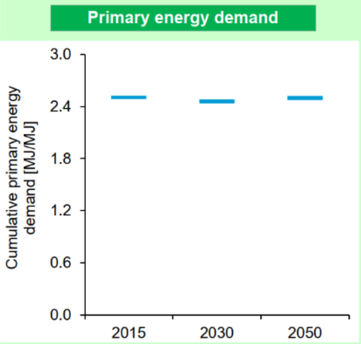
TRL-Level

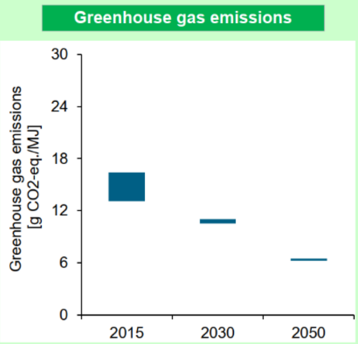
CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	7

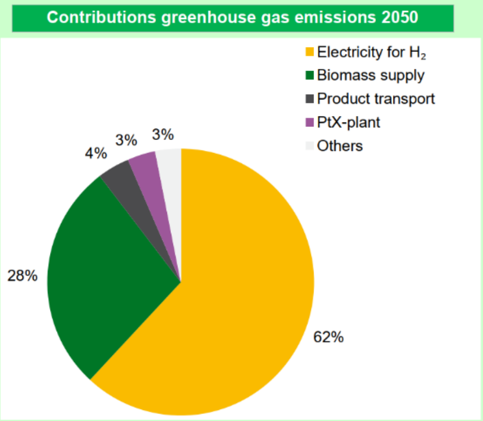
Life cycle assessment

Main contributions
- Electricity for H_2
- Biomass supply
- Product transport
- PtX-plant

Others include Auxiliaries, H_2-plant, Energie O_2+water


Primary energy demand

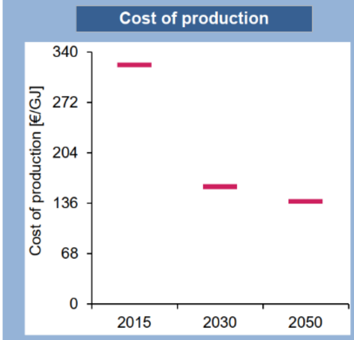

Greenhouse gas emissions

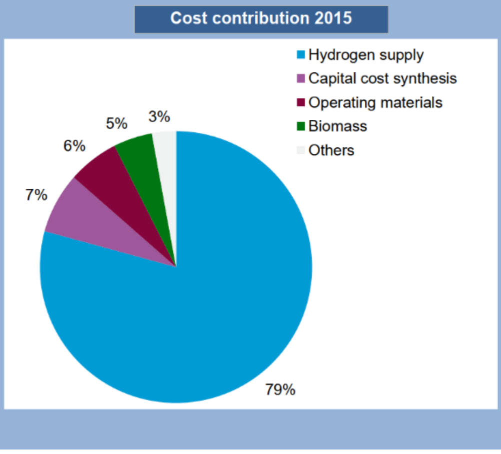

Contributions greenhouse gas emissions 2050

Estimated Cost

Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Biomass

Others include Fixed cost synthesis, Transport biomass, Transport


Cost of production


Cost contribution 2015

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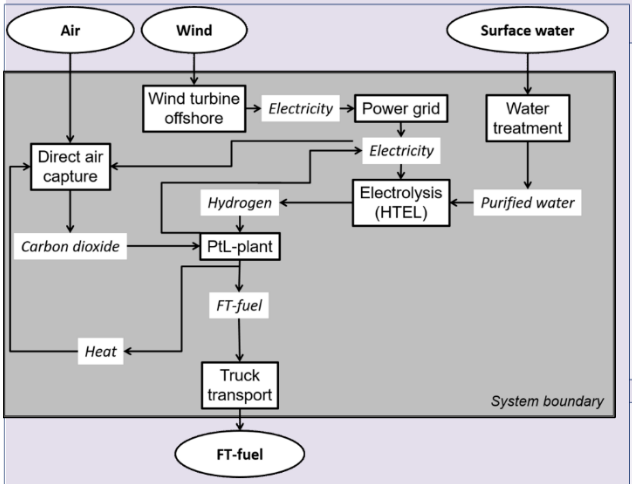
19_FT-Fuel/PtL/WindOFF/HTEL/DAC/Truck_D

Supply path



Description

The electricity is generated by offshore wind power plants in Germany and transferred to high-temperature electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is extracted from the air (DAC) using electricity from wind power. CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity from the PBtL plant is used in electrolysis. Excess heat is used for the DAC. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

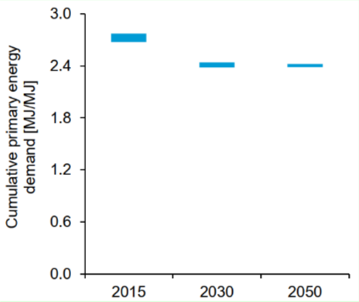
TRL-Level

CO2-Capturing	7
Electrolysis	n.a.
Synthesis	7

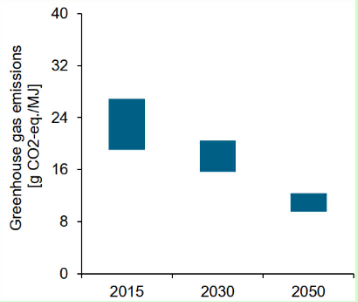
Life cycle assessment

Main contributions		**Others include**	
	Electricity for H_2 CO_2-plant Energy for CO_2 Product transport		PtX-plant, H_2-plant, Auxiliaries, Energie O_2+water

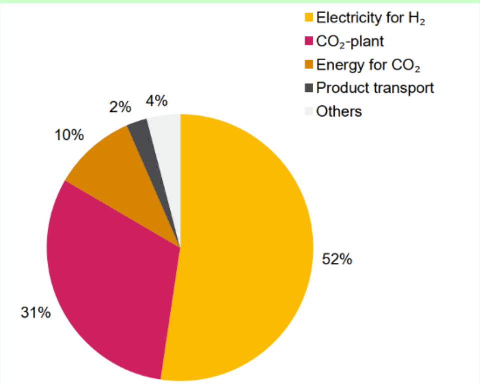
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

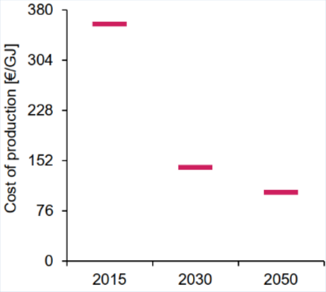


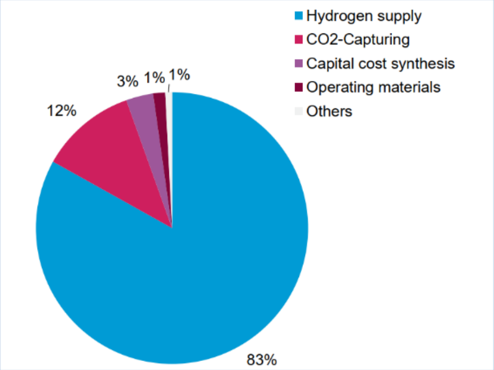
Estimated Cost

Main contributions		**Others include**	
	Hydrogen supply CO2-Capturing Capital cost synthesis Operating materials		Fixed cost synthesis, Transport

Cost contribution 2015

Cost of production





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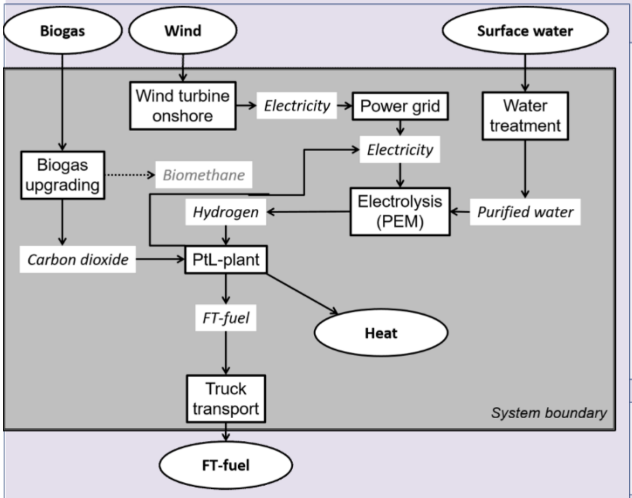
20_FT-Fuel/PtL/WindON/PEM/Biogas/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and transferred to the PEM electrolysis plant via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 from an existing biogas upgrading and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity generated by the PtL plant is used in electrolysis. The FT-fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

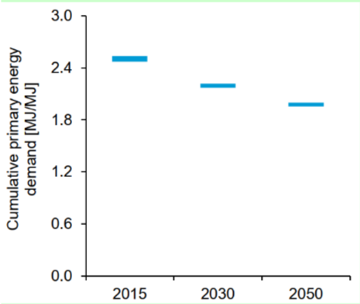
CO2-Capturing	9
Electrolysis	8
Synthesis	7

Life cycle assessment

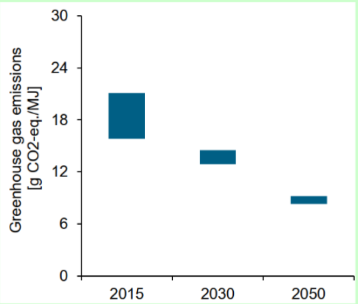
Main contributions
Electricity for H_2
CO_2-plant
H_2-plant
Product transport

Others include PtX-plant, Auxiliaries, Energie O_2+water

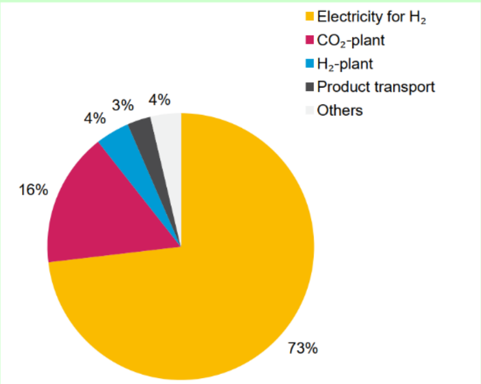
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

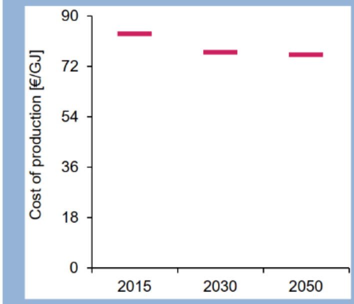


Estimated Cost

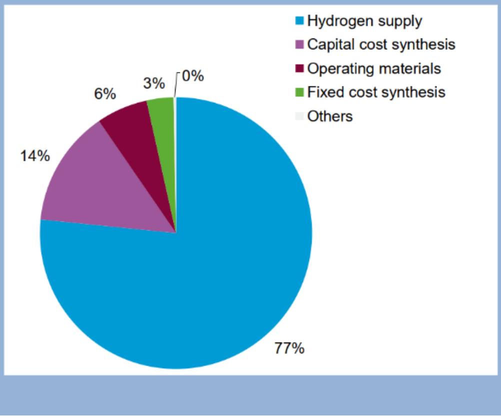
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include Transport

Cost of production



Cost contribution 2015



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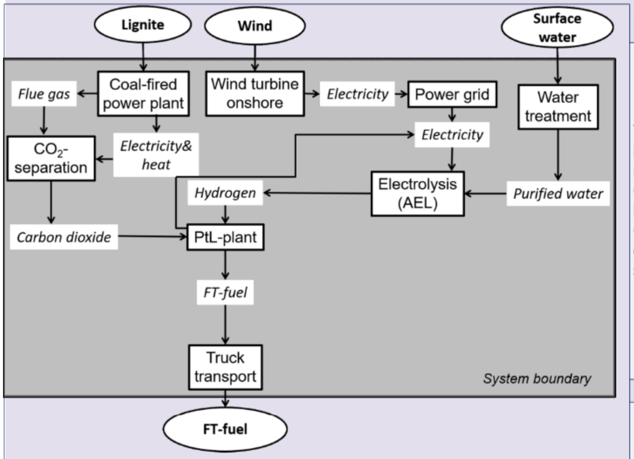
21_FT-Fuel/PtL/WindON/AEL/Lignite Power Plant/Truck_D

Supply path



Description

The electricity is generated from onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a lignite-fired power plant. Electricity and heat are obtained from the lignite-fired power plant as well.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity generated by the PtL plant is used in electrolysis. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

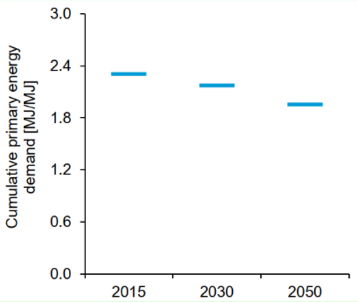
CO2-Capturing	9
Electrolysis	9
Synthesis	7

Life cycle assessment

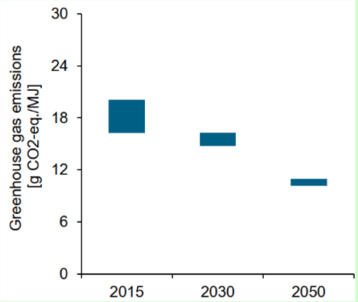
Main contributions
Electricity for H_2
Energy for CO_2
Auxiliaries
H_2-plant

Others include Product transport, PtX-plant, CO_2-plant, Energie O_2+water

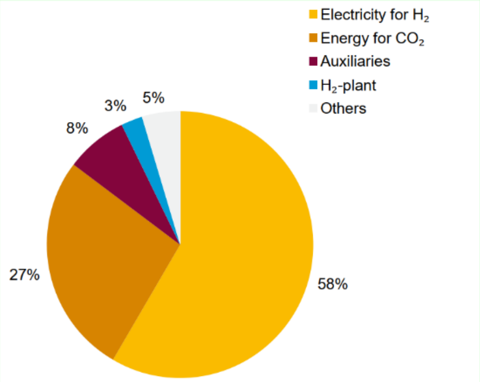
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

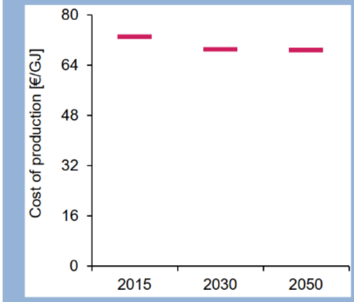


Estimated Cost

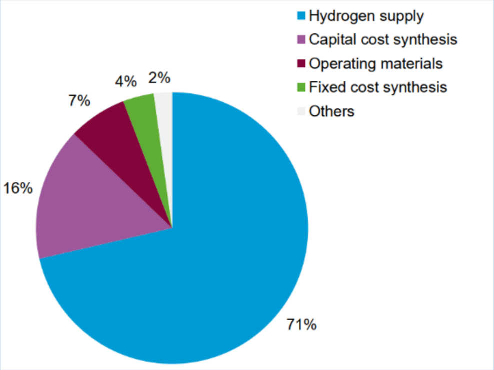
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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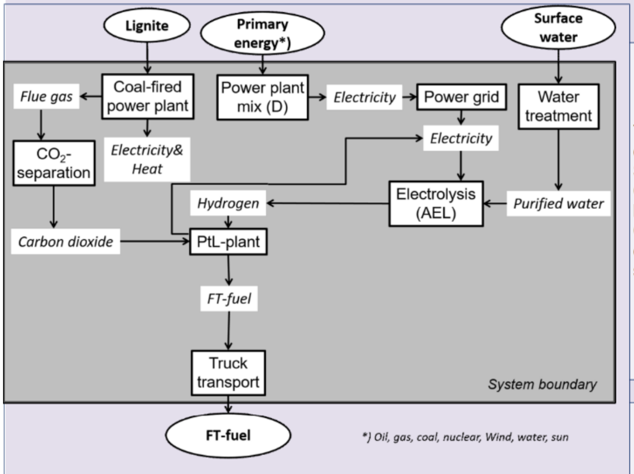
22_FT-Fuel/PtL/Grid Mix/AEL/Lignite Power Plant/Truck_D

Supply path



*) Oil, gas, coal, nuclear, Wind, water, sun

Description

The electricity is obtained from the electricity mix in Germany. The electricity is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is captured from flue gas of a lignite-fired power plant. Electricity and heat are obtained from the lignite-fired power plant as well. CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity generated by the PtL plant is used in electrolysis. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	75%
Investment cost [Mio. €]	344

TRL-Level

CO2-Capturing	9
Electrolysis	9
Synthesis	7

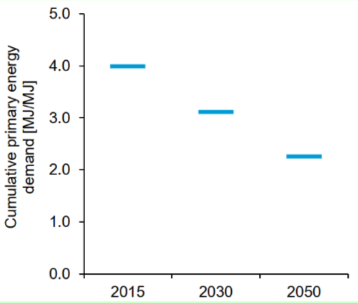
Life cycle assessment

Main contributions

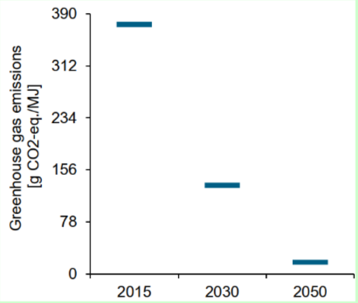
- Electricity for H_2
- Energy for CO_2
- Auxiliaries
- H_2-plant

Others include Product transport, PtX-plant, CO_2-plant, Energie O_2+water

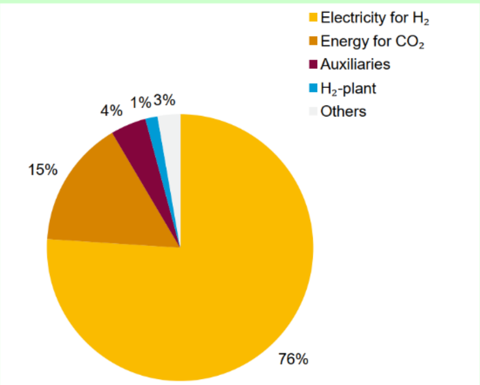
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



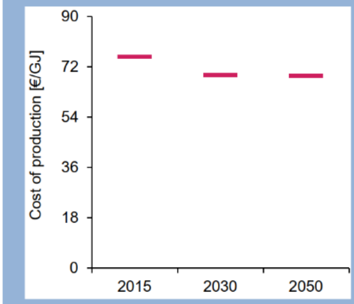
Estimated Cost

Main contributions

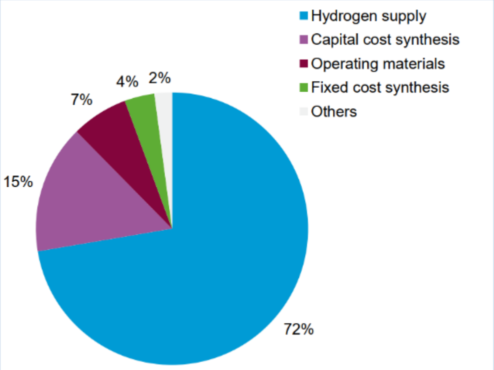
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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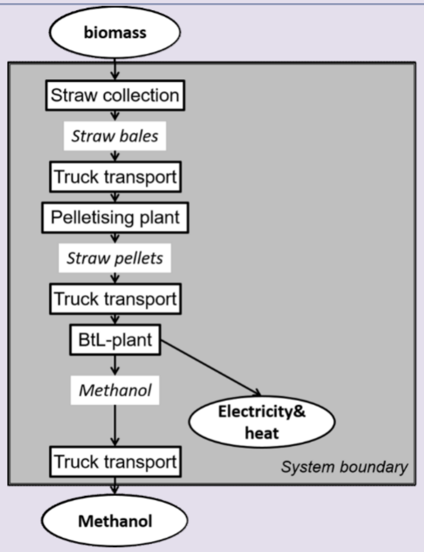
23_Methanol/BtL/Straw/Truck_D

Supply path



Description

Straw from grain farming in Germany is collected in bales and transported to the pelleting plant. The straw pellets are transported to the BtL plant. The straw pellets are gasified in the BtL plant and converted into methanol. The excess electricity and excess heat generated are used otherwise. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	383

TRL-Level

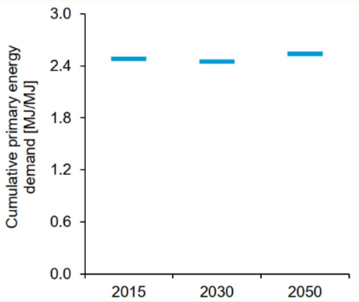
CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	8

Life cycle assessment

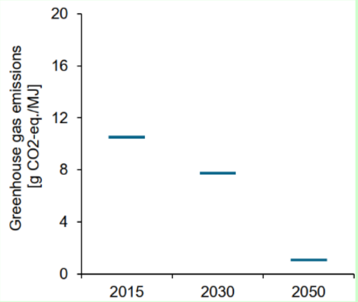
Main contributions
- Product transport
- PtX-plant
- Biomass supply
- Auxiliaries

Others include none

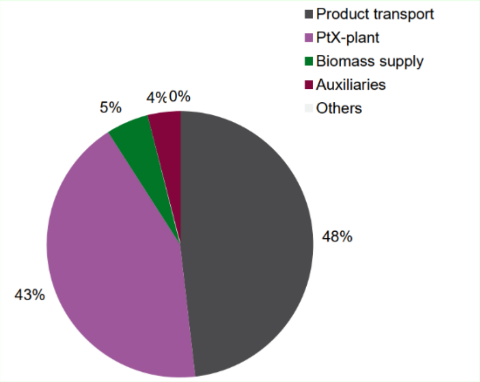
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



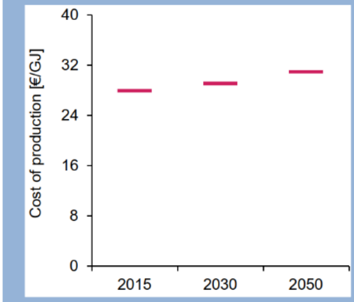
Estimated Cost

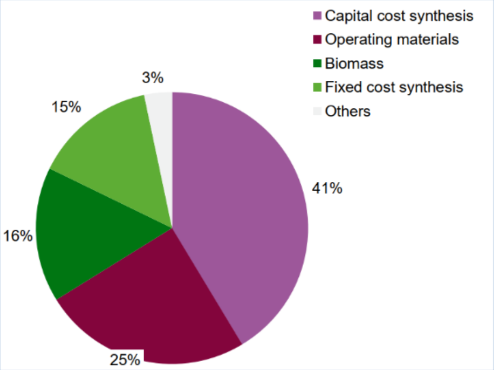
Main contributions
- Capital cost synthesis
- Operating materials
- Biomass
- Fixed cost synthesis

Others include Transport biomass, Transport

Cost contribution 2015

Cost of production





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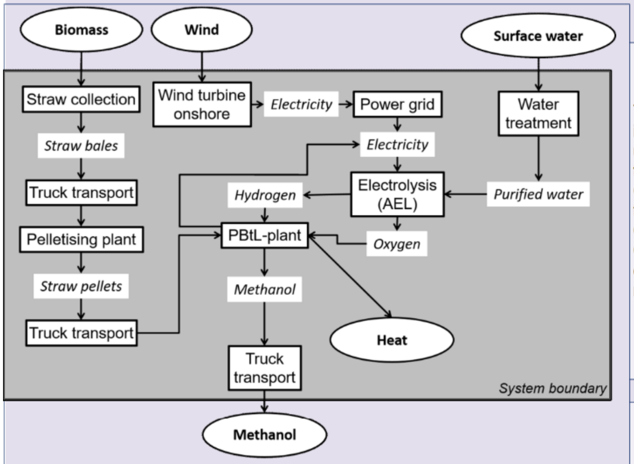
24_Methanol/PBtL/WindON/Straw/AEL/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. Generated oxygen is used in the gasification process. Straw from grain farming is collected in bales in Germany and transported to the pelleting plant. The straw pellets are transported to the BtL plant.
CO2 is obtained from the gasification of straw in the PBtL plant.
CO2 and hydrogen are used in the PBtL plant to produce methanol. Excess electricity is used in electrolysis. Excess heat is used otherwise. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	510

TRL-Level

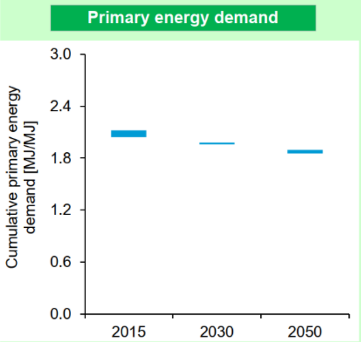
CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

Life cycle assessment

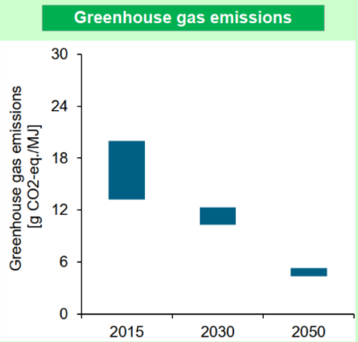
Main contributions
- Electricity for H_2
- Product transport
- PtX-plant
- Auxiliaries

Others include H_2-plant, Energie O_2+water, Biomass supply

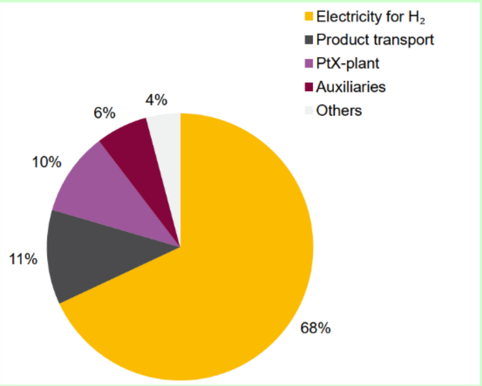
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

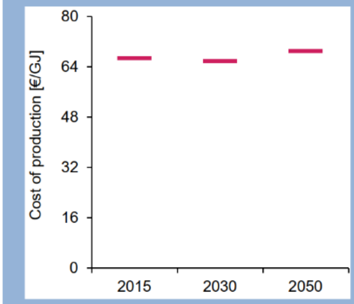


Estimated Cost

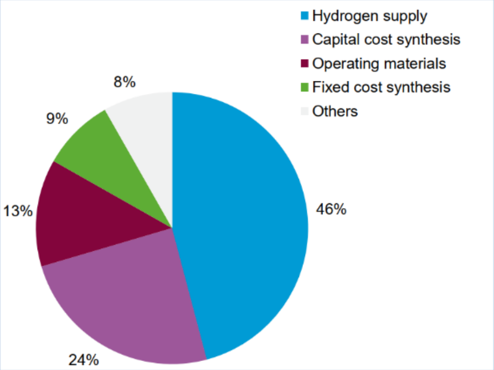
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include Biomass, Transport biomass, Transport

Cost of production



Cost contribution 2015



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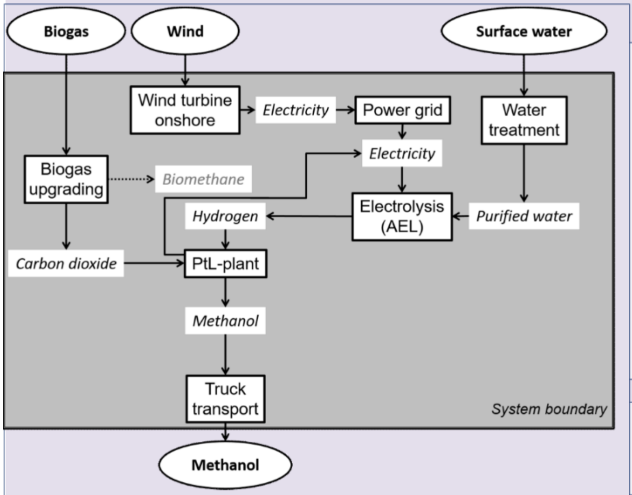
25_Methanol/PtL/WindON/AEL/Biogas/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 from an existing biogas upgrading plant and hydrogen are used in the PtL plant to produce methanol. The generated electricity goes to the electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

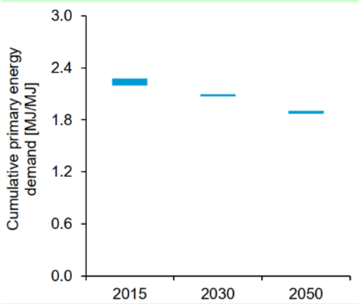
CO2-Capturing	9
Electrolysis	9
Synthesis	7

Life cycle assessment

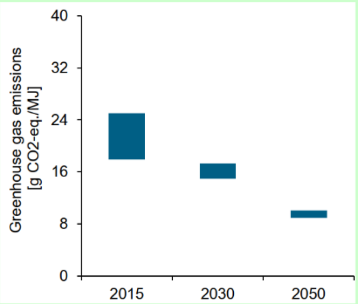
Main contributions
Electricity for H_2
CO_2-plant
Product transport
Auxiliaries

Others include PtX-plant, H_2-plant, Energie O_2+water, Energy for CO_2

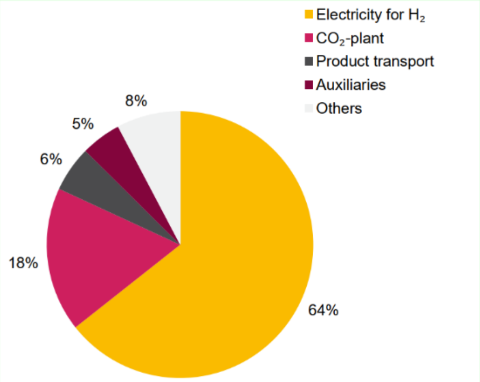
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

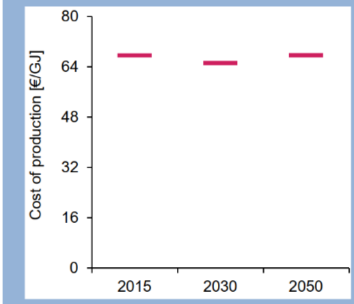


Estimated Cost

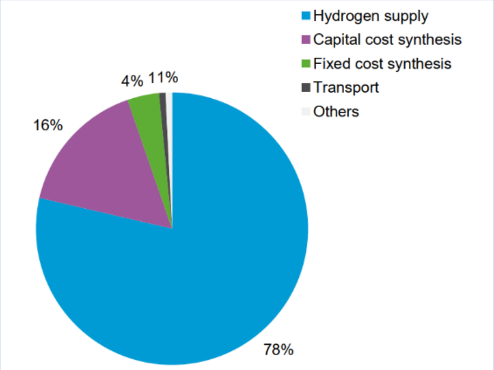
Main contributions
Hydrogen supply
Capital cost synthesis
Fixed cost synthesis
Transport

Others include Operating materials

Cost of production



Cost contribution 2015



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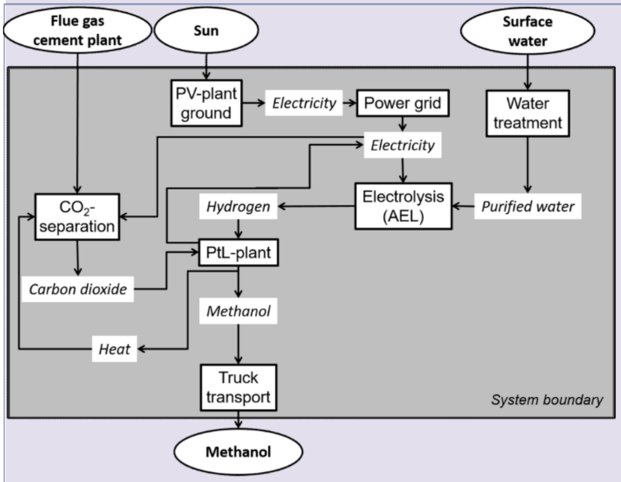
26_Methanol/PtL/PVground/AEL/Cement/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used for the CO2 capture. Excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	7

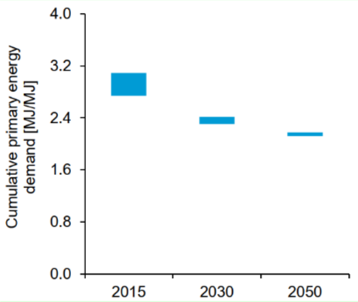
Life cycle assessment

Main contributions

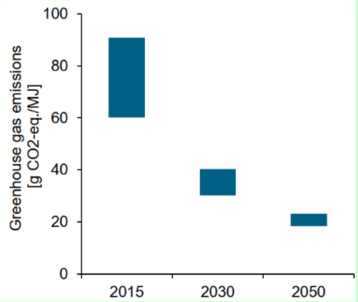
- Electricity for H_2
- Auxiliaries
- Energy for CO_2
- Product transport

Others include PtX-plant, H_2-plant, Energie O_2+water, CO_2-plant

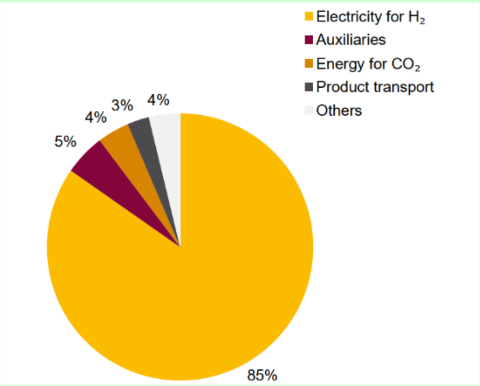
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



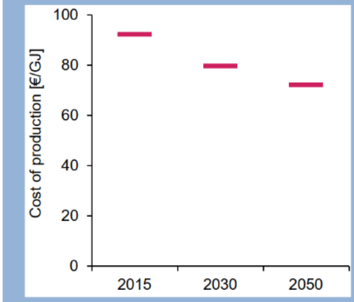
Estimated Cost

Main contributions

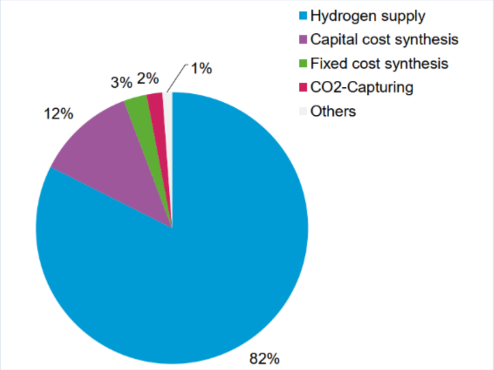
- Hydrogen supply
- Capital cost synthesis
- Fixed cost synthesis
- CO2-Capturing

Others include Transport, Operating materials

Cost of production



Cost contribution 2015



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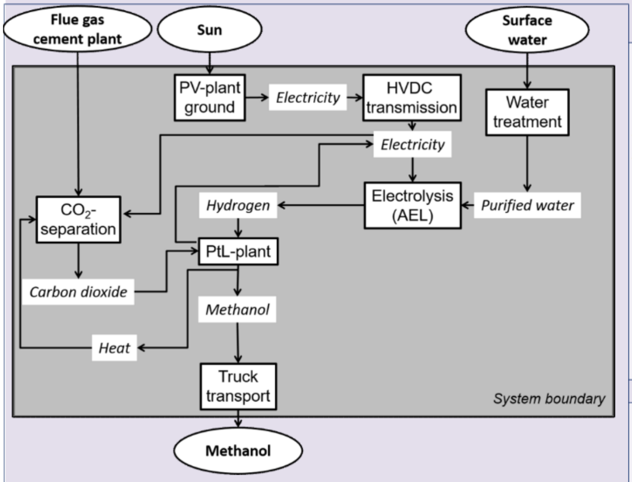
27_Methanol/PtL/PVground/AEL/Cement/HVDC+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and is transferred to the alkaline electrolysis in Germany via the HVDC grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used for CO2 capture. Excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

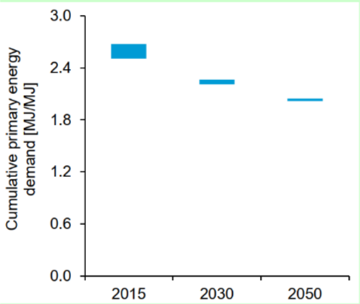
TRL-Level

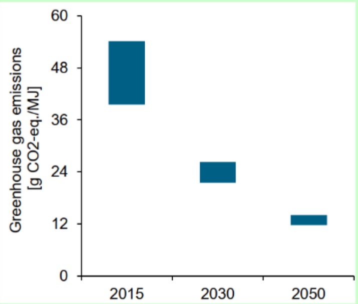
CO2-Capturing	8
Electrolysis	9
Synthesis	7

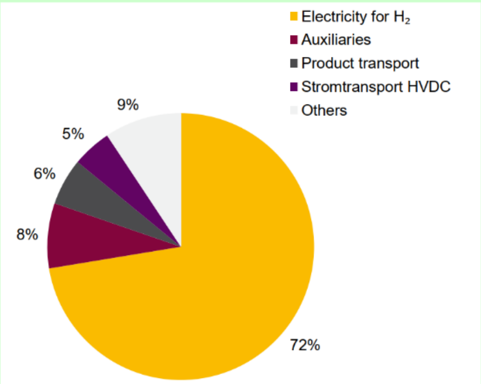
Life cycle assessment

Main contributions
- Electricity for H_2
- Auxiliaries
- Product transport
- Stromtransport HVDC

Others include PtX-plant, Energy for CO_2, H_2-plant, Energie O_2+water, CO_2-plant


Primary energy demand

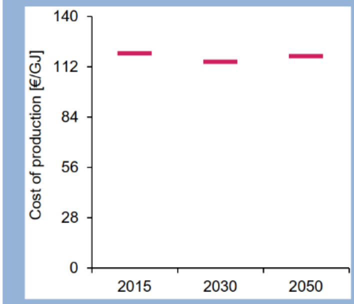

Greenhouse gas emissions

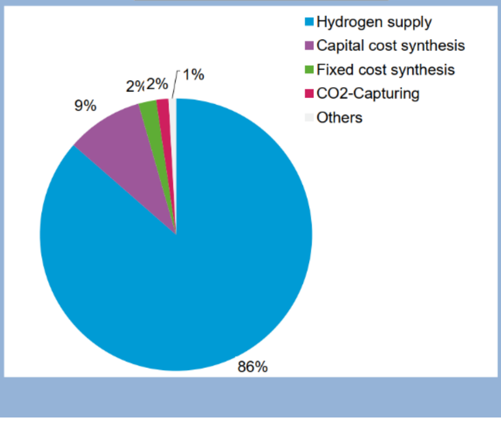

Contributions greenhouse gas emissions 2050

Estimated Cost

Main contributions
- Hydrogen supply
- Capital cost synthesis
- Fixed cost synthesis
- CO2-Capturing

Others include Transport, Operating materials


Cost of production


Cost contribution 2015

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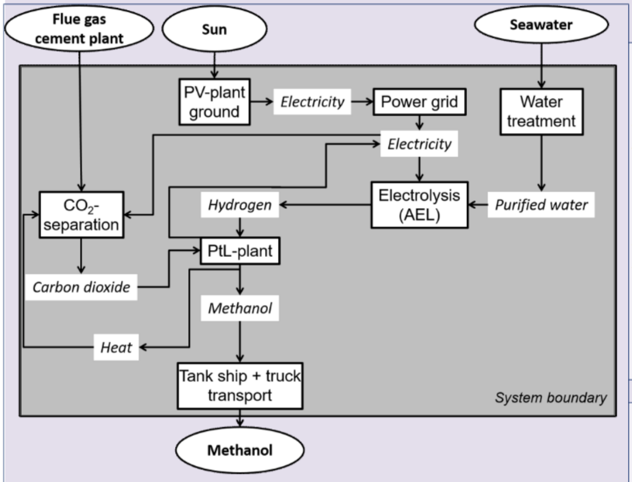
28_Methanol/PtL/PVground/AEL/Cement/Tanker+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used for the CO2 capture. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

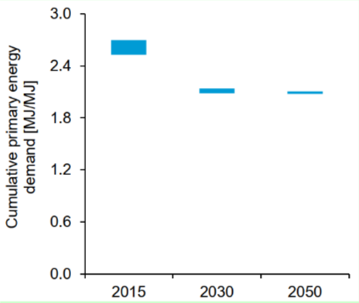
CO2-Capturing	8
Electrolysis	9
Synthesis	7

Life cycle assessment

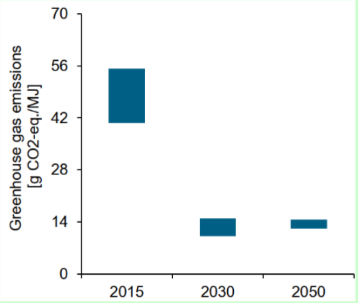
Main contributions
Electricity for H_2
Product transport
Auxiliaries
PtX-plant

Others include Energy for CO_2, H_2-plant, Energie O_2+water, CO_2-plant

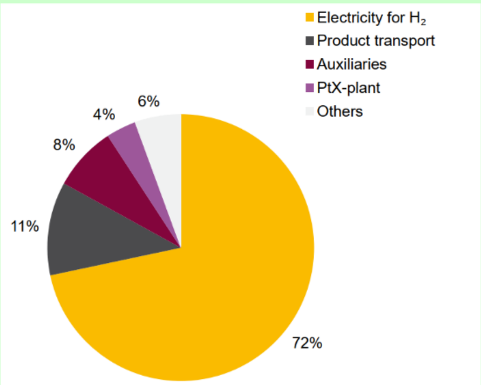
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

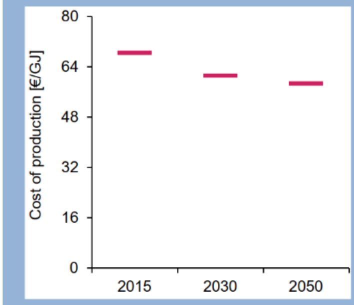


Estimated Cost

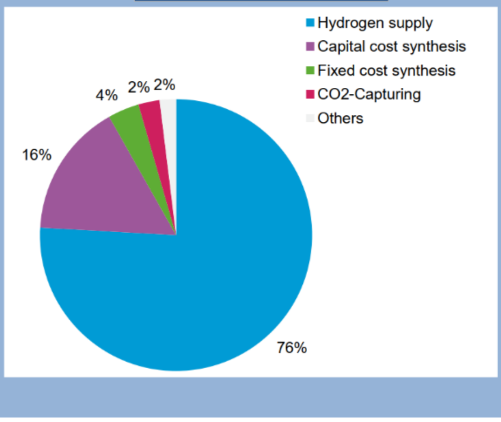
Main contributions
Hydrogen supply
Capital cost synthesis
Fixed cost synthesis
CO2-Capturing

Others include Transport, Operating materials

Cost of production



Cost contribution 2015



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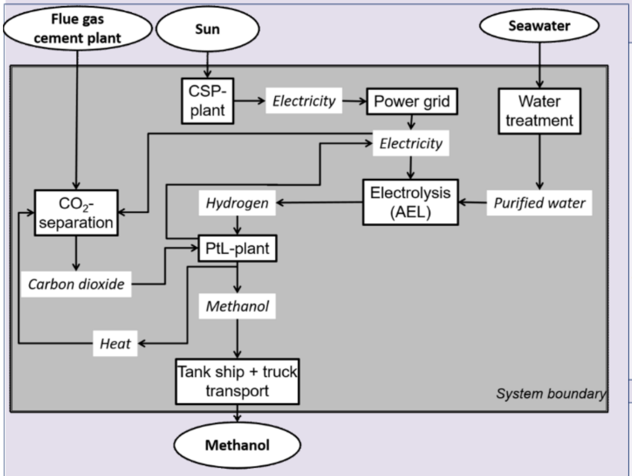
29_Methanol/PtL/CSP/AEL/Cement/Tanker+Truck_Saudi Arabia

Supply path



Description

The electricity is generated by a CSP power plant in Saudi Arabia and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a cement factory using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used for CO2 capture. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	7

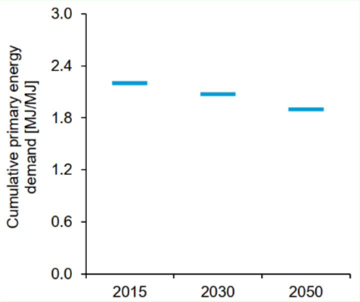
Life cycle assessment

Main contributions

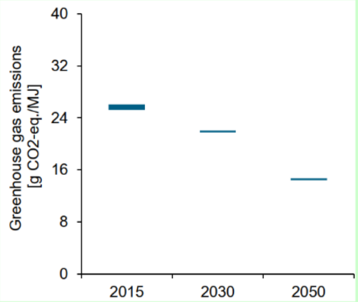
- Electricity for H_2
- Product transport
- Auxiliaries
- Energy for CO_2

Others include PtX-plant, H_2-plant, Energie O_2+water, CO_2-plant

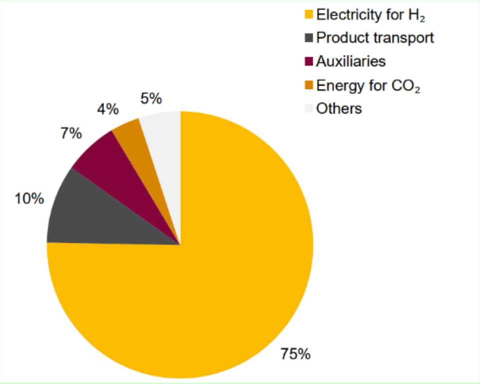
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



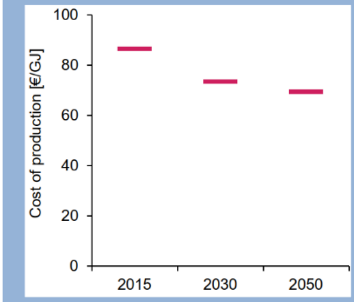
Estimated Cost

Main contributions

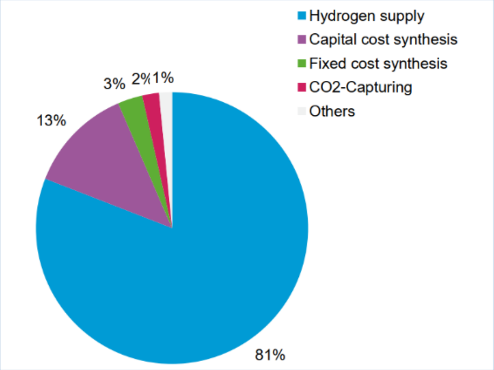
- Hydrogen supply
- Capital cost synthesis
- Fixed cost synthesis
- CO2-Capturing

Others include Transport, Operating materials

Cost of production



Cost contribution 2015



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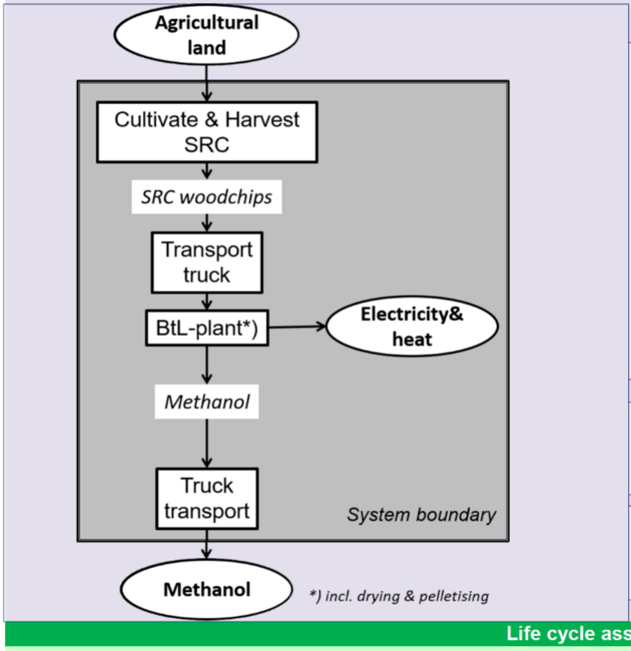
30_Methanol/BtL/SRC Pellets/Truck_D

Supply path



Description

Wood from a short rotation plantation is used to produce wood chips in Germany. It is transported to the BtL plant via truck.
The biomass is gasified to methanol in the BtL plant. Excess electricity generated and excess heat is used otherwise. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	383

TRL-Level

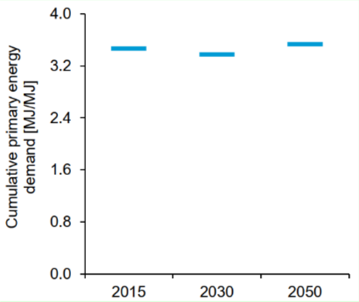
CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	8

Life cycle assessment

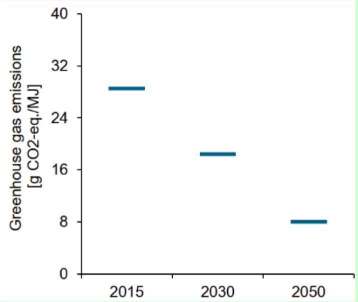
Main contributions
- Biomass supply
- Energie O_2+water
- Product transport
- PtX-plant

Others include Auxiliaries

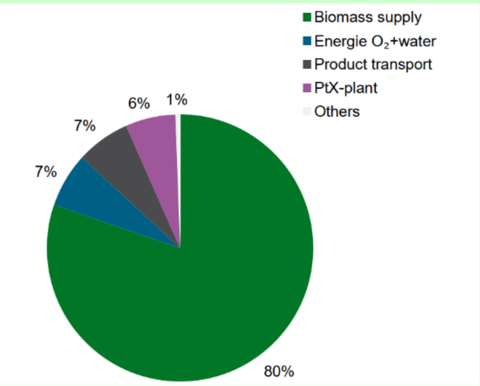
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

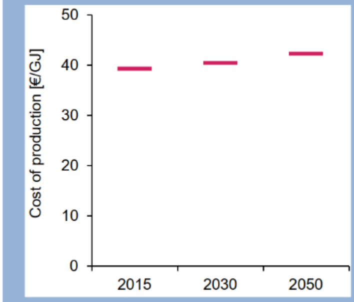


Estimated Cost

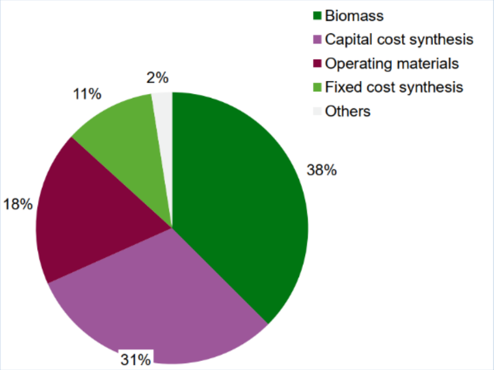
Main contributions
- Biomass
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include Transport biomass, Transport

Cost of production



Cost contribution 2015



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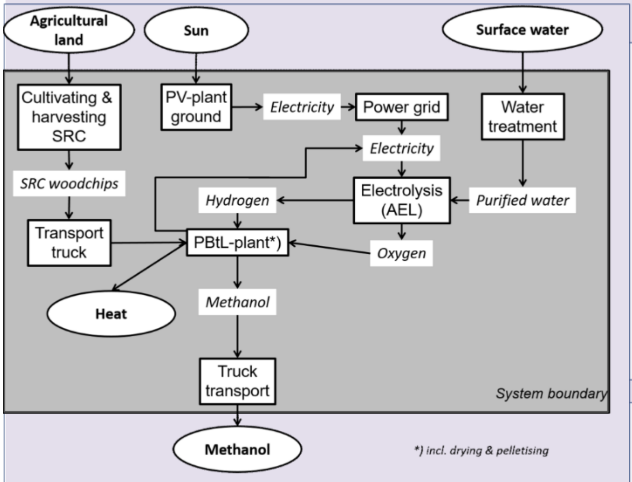
31_Methanol/PBtL/PVground/SRC Pellets/AEL/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. The oxygen output can be used in the gasification in the BPtL plant. Wood from a short rotation plantation in Germany is used to produce wood chips. They are transported to the PBtL plant by truck.
CO2 is captured from gasification of the pellets from short rotation plantations in the BPtL plant.
CO2 and hydrogen are used for the production of methanol in the PtL plant. Excess heat can be used otherwise. The electricity is used in electrolysis.
The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	510

TRL-Level

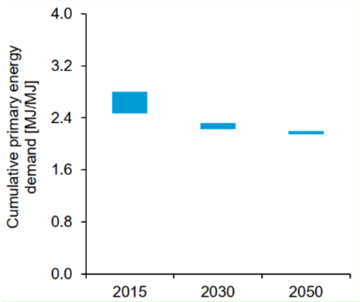
CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

Life cycle assessment

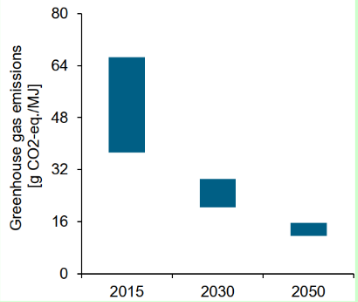
Main contributions
Electricity for H_2
Biomass supply
Product transport
PtX-plant

Others include Auxiliaries, H_2-plant, Energie O_2+water

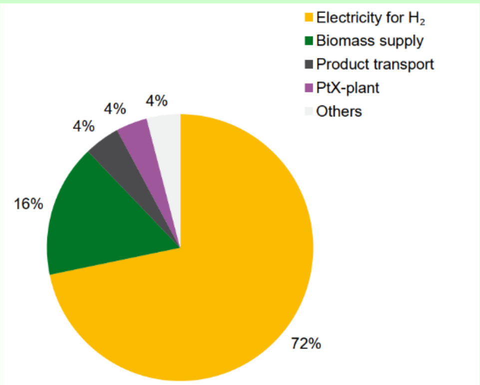
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

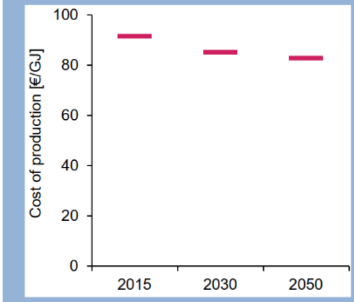


Estimated Cost

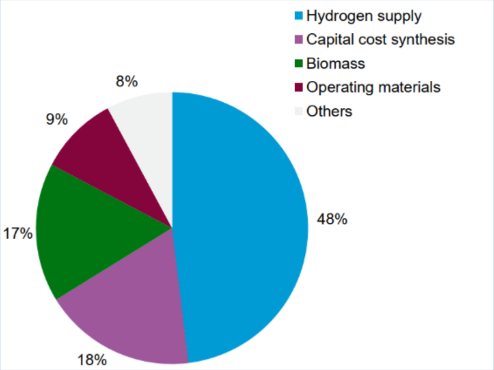
Main contributions
Hydrogen supply
Capital cost synthesis
Biomass
Operating materials

Others include Fixed cost synthesis, Transport biomass, Transport

Cost of production



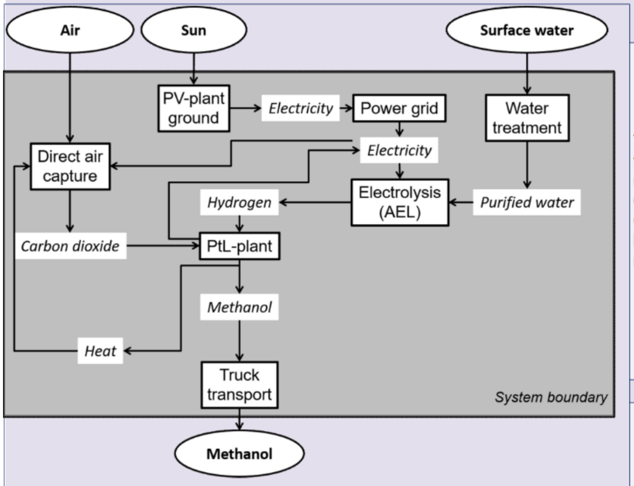
Cost contribution 2015



Stand 18.02.2020

32_Methanol/PtL/PVground/AEL/DAC/Truck_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from PV.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The methanol is stored and then transported via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

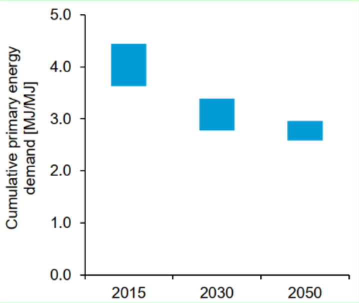
CO2-Capturing	7
Electrolysis	9
Synthesis	7

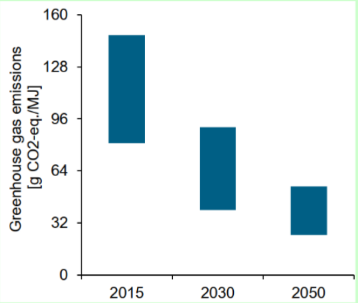
Life cycle assessment

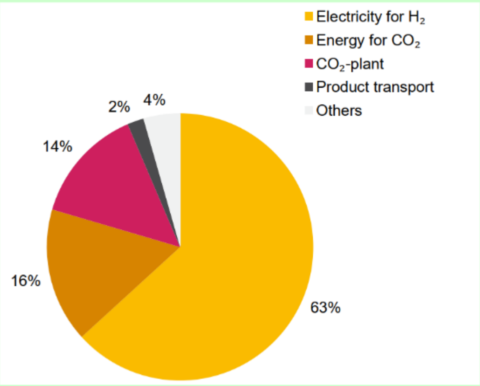
Main contributions

- Electricity for H_2
- Energy for CO_2
- CO_2-plant
- Product transport

Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water


Primary energy demand


Greenhouse gas emissions

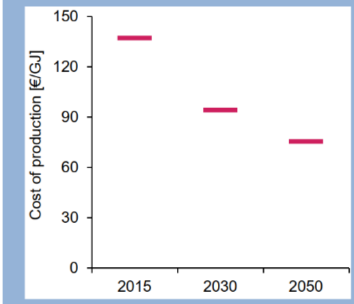

Contributions greenhouse gas emissions 2050

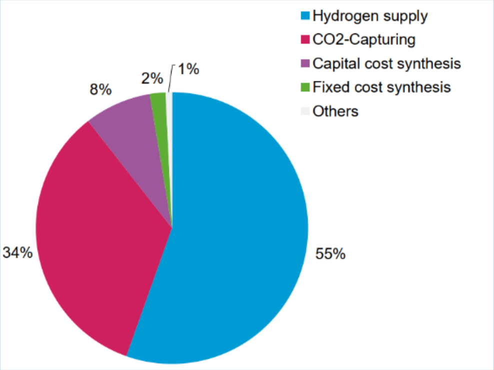
Estimated Cost

Main contributions

- Hydrogen supply
- CO2-Capturing
- Capital cost synthesis
- Fixed cost synthesis

Others include Transport, Operating materials


Cost of production


Cost contribution 2015

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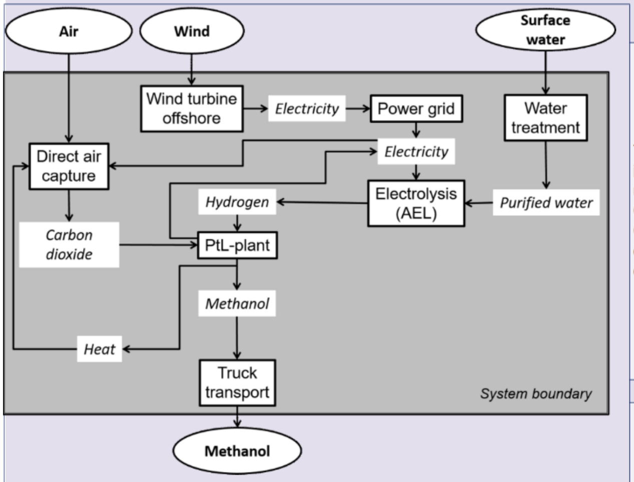
33_Methanol/PtL/WindOFF/AEL/DAC/Truck_D

Supply path



Description

The electricity is generated by offshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from wind power.
CO2 and hydrogen are used in the PtL plant to produce methanol. The excess heat is used in the DAC. The excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

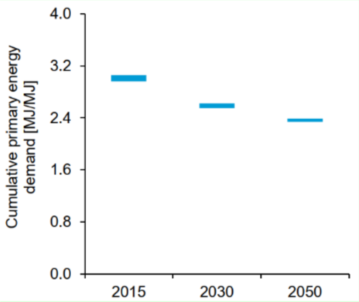
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

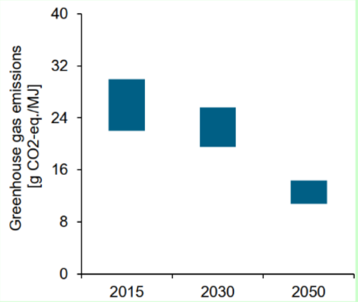
Main contributions
- Electricity for H_2
- CO_2-plant
- Energy for CO_2
- Product transport

Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water

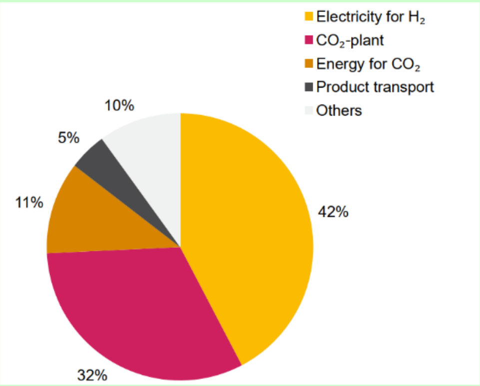
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

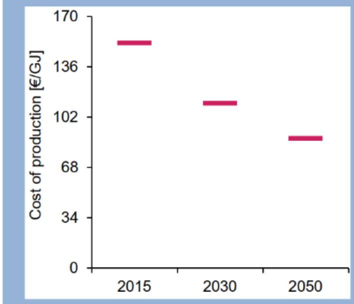


Estimated Cost

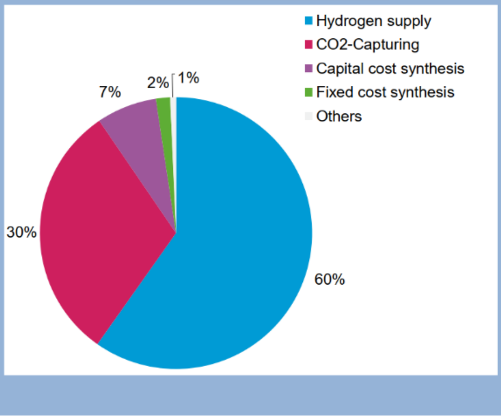
Main contributions
- Hydrogen supply
- CO2-Capturing
- Capital cost synthesis
- Fixed cost synthesis

Others include Transport, Operating materials

Cost of production



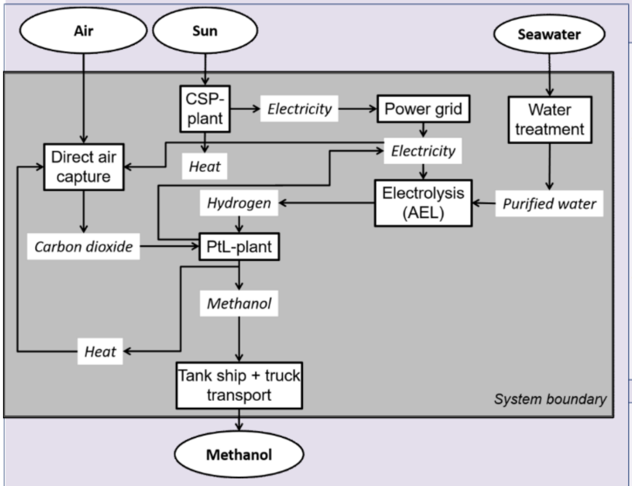
Cost contribution 2015



Stand 18.02.2020

34_Methanol/PtL/CSP/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by a CSP power plant in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

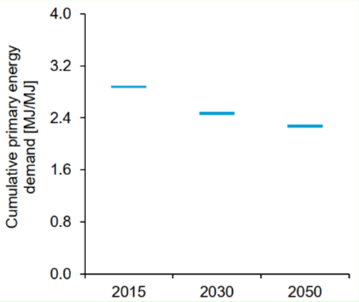
Main contributions

Electricity for H_2
CO_2-plant
Energy for CO_2
Product transport

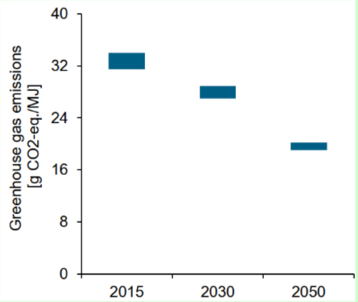
Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water

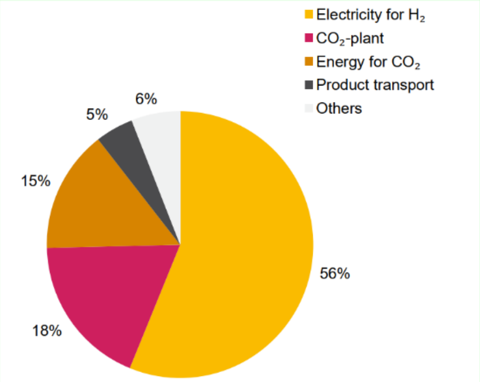
Contributions greenhouse gas emissions 2050

Primary energy demand



Greenhouse gas emissions





Estimated Cost

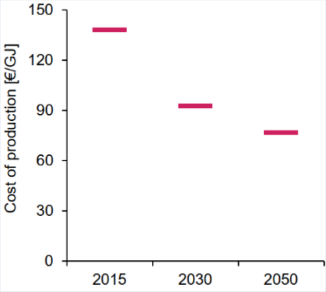
Main contributions

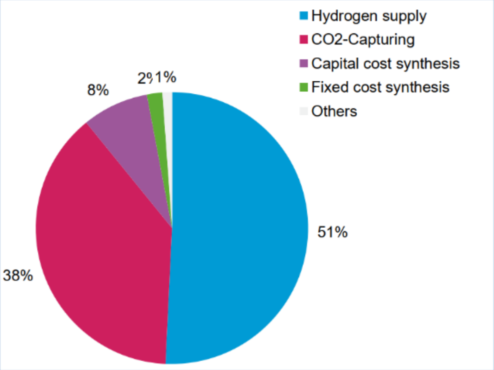
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Fixed cost synthesis

Others include Transport, Operating materials

Cost contribution 2015

Cost of production

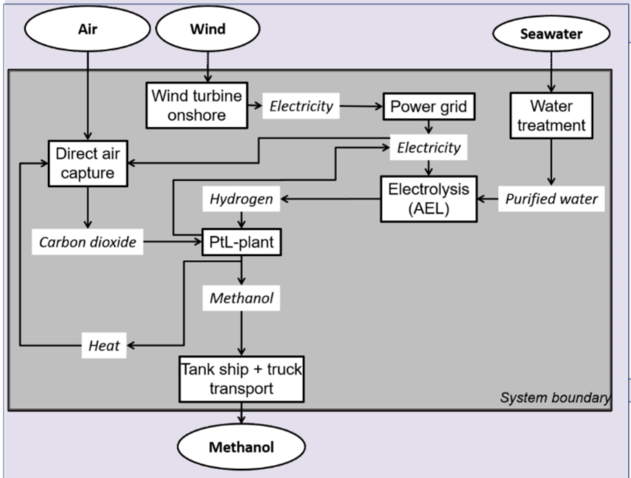




Stand 18.02.2020

35_Methanol/PtL/WindON/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by onshore wind power plants in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from wind power. CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

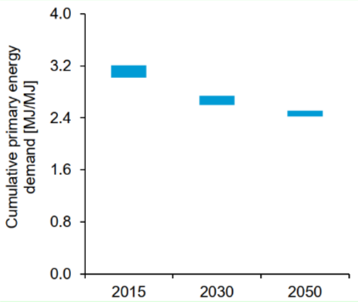
Life cycle assessment

Main contributions

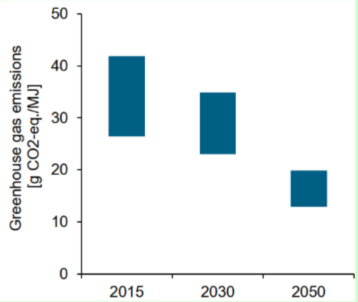
- Electricity for H_2
- CO_2-plant
- Energy for CO_2
- Product transport

Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water

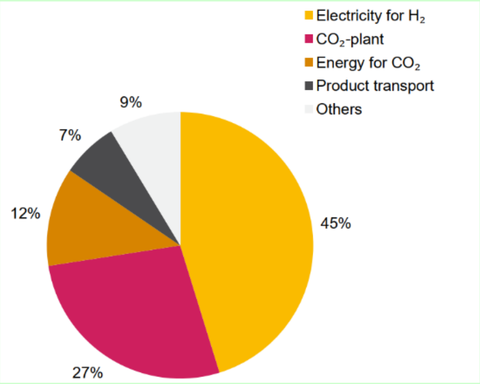
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



Estimated Cost

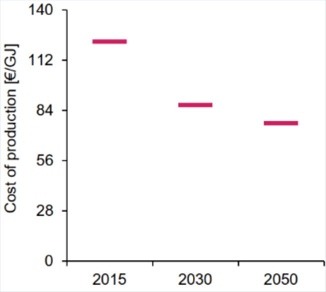
Main contributions

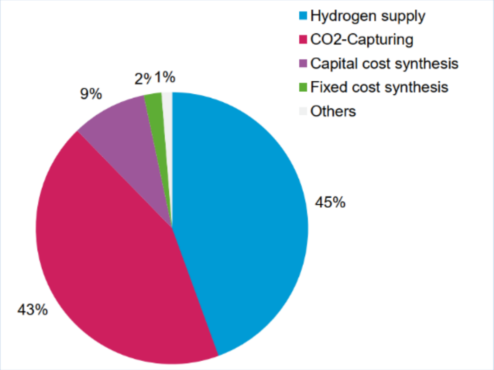
- Hydrogen supply
- CO2-Capturing
- Capital cost synthesis
- Fixed cost synthesis

Others include Transport, Operating materials

Cost contribution 2015

Cost of production

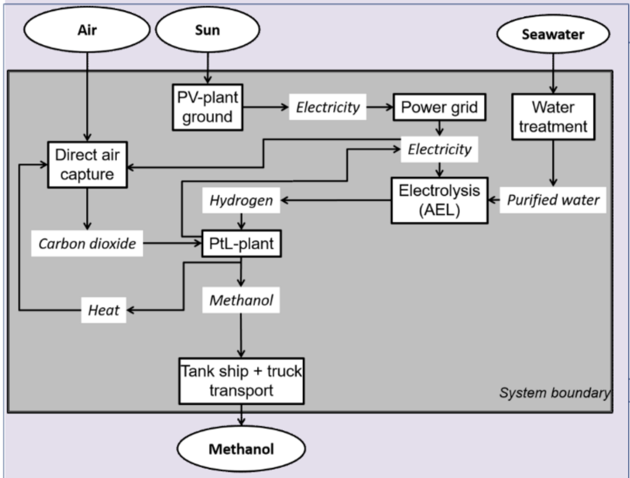




Stand 18.02.2020

36_Methanol/PtL/PVground/AEL/DAC/Tanker+Truck_Morocco

Supply path



Description

The electricity is generated by ground mounted PV in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from PV.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

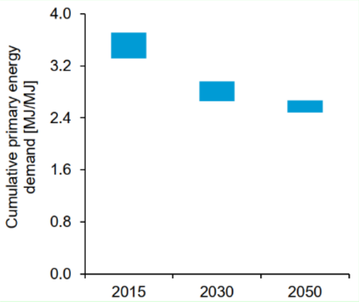
Life cycle assessment

Main contributions

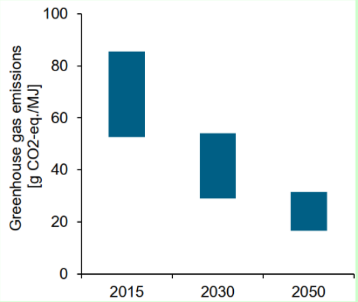
Electricity for H_2
CO_2-plant
Energy for CO_2
Product transport

Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water

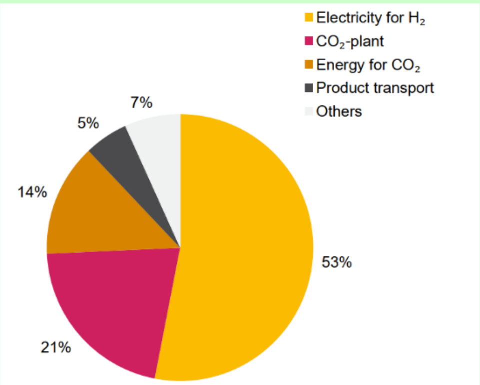
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



Estimated Cost

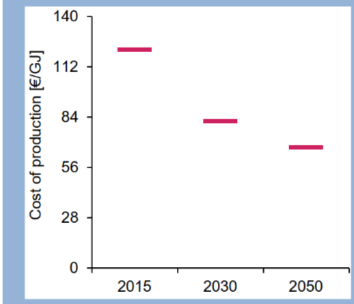
Main contributions

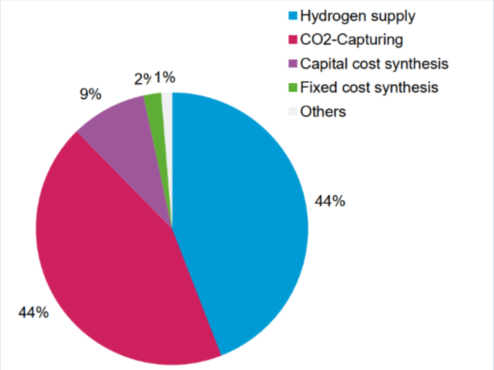
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Fixed cost synthesis

Others include Transport, Operating materials

Cost contribution 2015

Cost of production

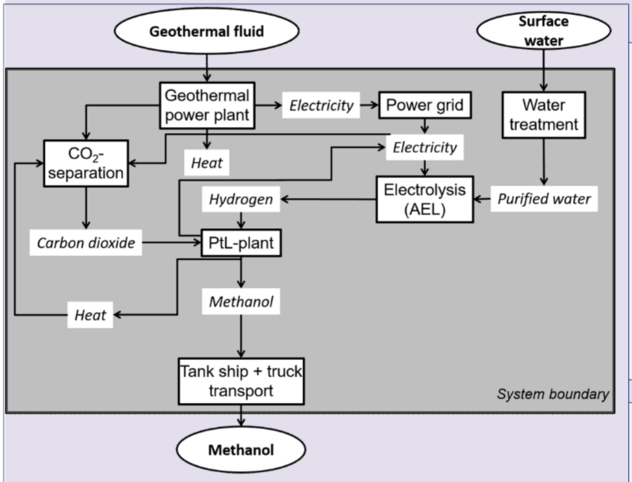




Stand 18.02.2020

37_Methanol/PtL/Geothermal/AEL/Geothermal/Tanker+Truck_Iceland

Supply path



Description

The electricity is generated in a geothermal power plant in Iceland and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the geothermal fluid using heat and electricity from geothermal energy.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess electricity is used in the electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

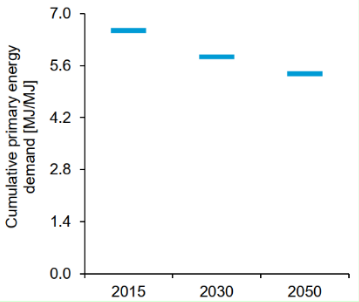
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

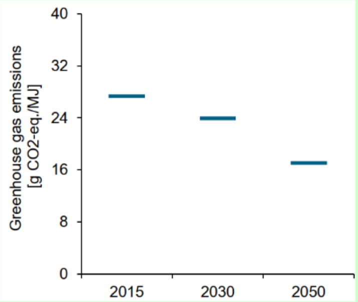
Main contributions
- Electricity for H_2
- CO_2-plant
- Energy for CO_2
- Product transport

Others include PtX-plant, Auxiliaries, H_2-plant, Energie O_2+water

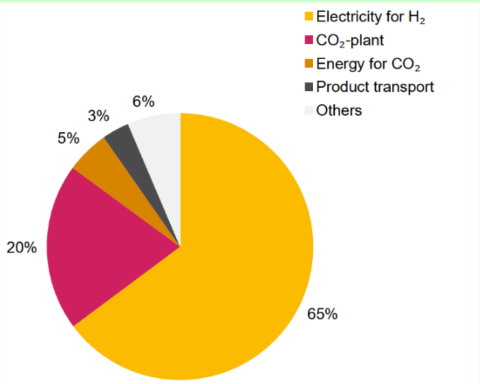
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

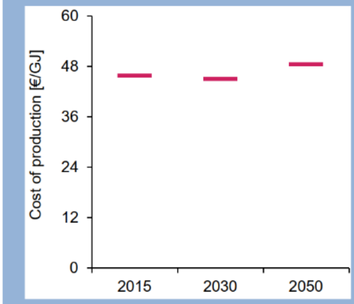


Estimated Cost

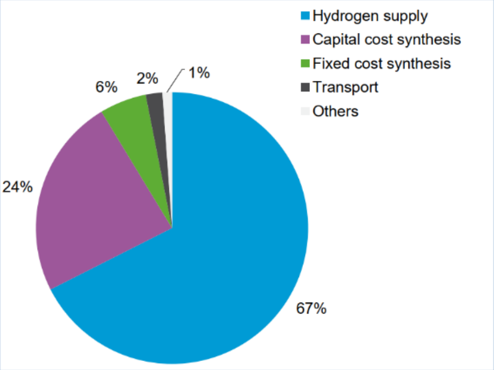
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Fixed cost synthesis
- Transport

Others include Operating materials

Cost of production



Cost contribution 2015



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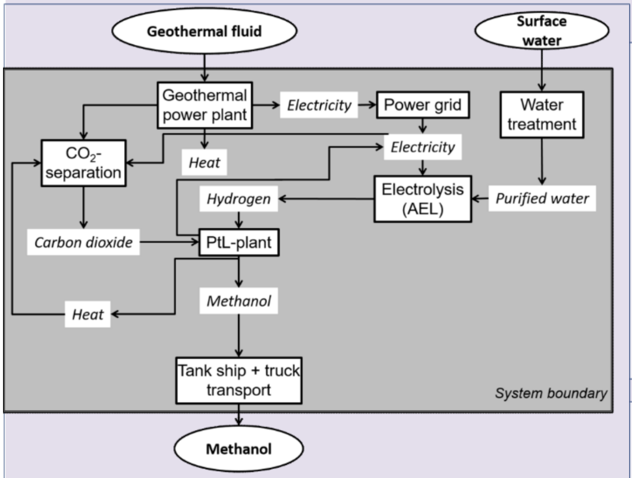
38_Methanol/PBtL/Hydro/Residual Forrest Wood /AEL/Tanker+Truck_Sweden

Supply path



Description

The electricity is generated by a hydro electric power plant in Sweden and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. The generated oxygen is used in the gasification process. The residual forest wood is collected and transported to the PBtL plant by truck.
CO2 is captured from the gasification of the residual forest wood in the BPtL plant.
CO2 and hydrogen are used in the PBtL plant to produce methanol. Excess heat is used otherwise. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	510

TRL-Level

CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

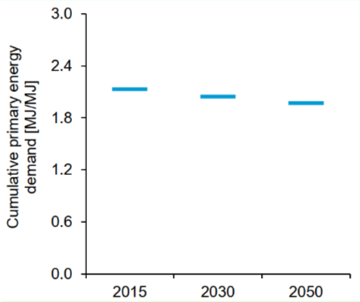
Life cycle assessment

Main contributions

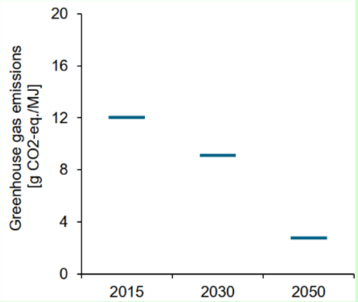
- Electricity for H_2
- Product transport
- PtX-plant
- Auxiliaries

Others include H_2-plant, Biomass supply, Energie O_2+water

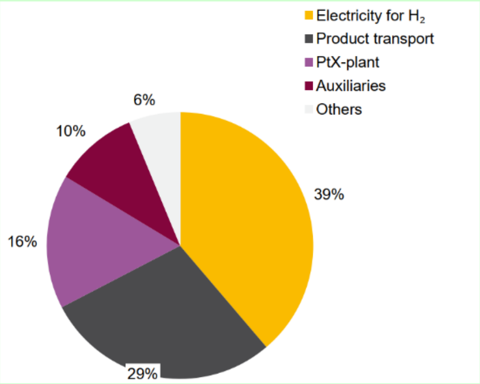
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



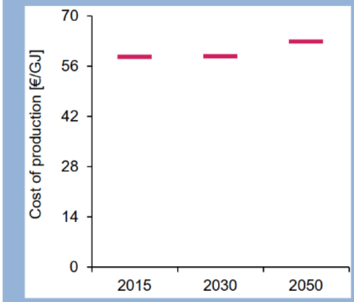
Estimated Cost

Main contributions

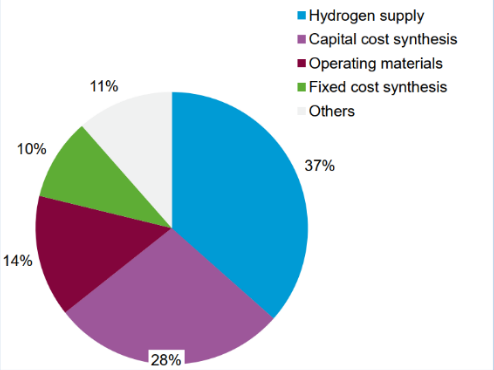
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include Biomass, Transport, Transport biomass

Cost of production



Cost contribution 2015



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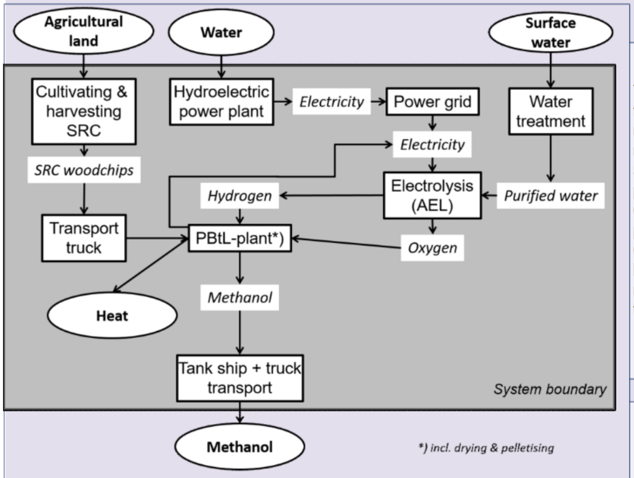
39_Methanol/PBtL/Hydro/SRC Pellets/AEL/Tanker+Truck_Sweden

Supply path



Description

The electricity is generated by a hydro electric power plant in Sweden and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. The generaated oxygen is used in the gasification process. Wood from a short rotation plantation in Sweden is used to produce wood chips. They are transported to the PBtL plant by truck.
CO2 is captured from the gasification of pellets from short rotation plantations in the PBtL plant.
CO2 and hydrogen are used in the PBtL plant to produce methanol. Excess heat is used otherwise. Excess electricity is used in electrolysis. The methanol is stored, then brought to Germany by tanker and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	68%
Investment cost [Mio. €]	510

TRL-Level

CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

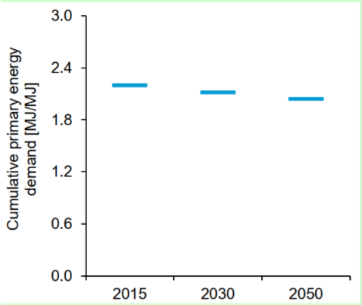
Life cycle assessment

Main contributions

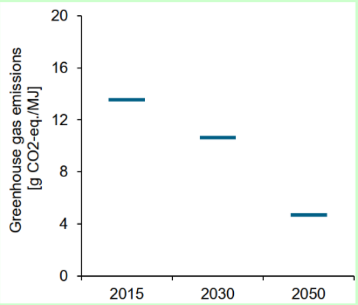
- Biomass supply
- Electricity for H_2
- Product transport
- PtX-plant

Others include Auxiliaries, H_2-plant, Energie O_2+water

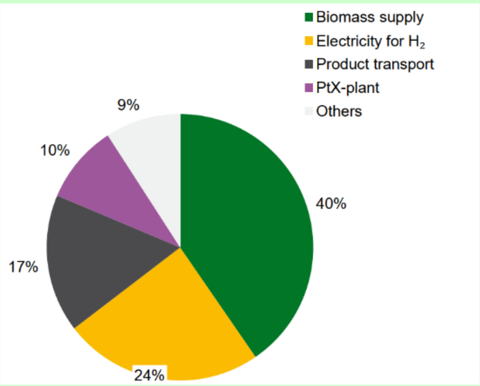
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



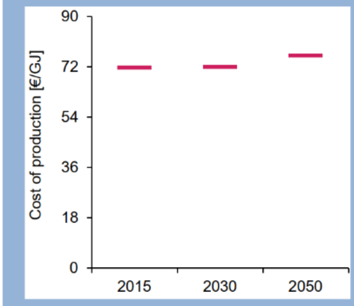
Estimated Cost

Main contributions

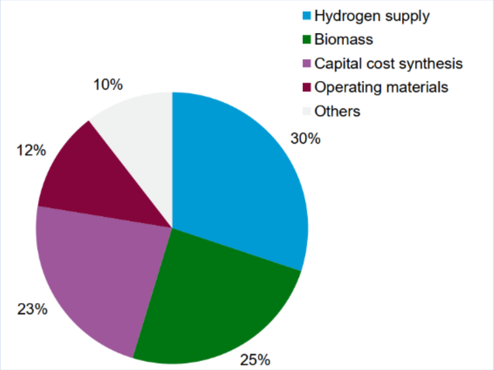
- Hydrogen supply
- Biomass
- Capital cost synthesis
- Operating materials

Others include Fixed cost synthesis, Transport, Transport biomass

Cost of production



Cost contribution 2015



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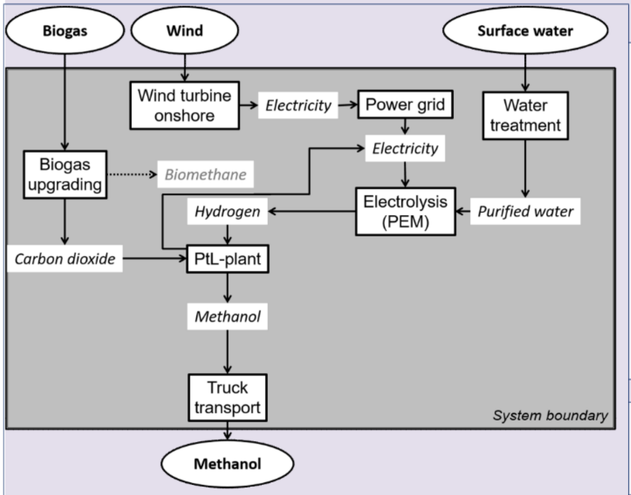
40_Methanol/PtL/WindON/PEM/Biogas/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and transported to the PEM electrolysis plant via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 from an existing biogas upgrading plant is used. CO2 and hydrogen are used in the PtL plant to produce methanol. Excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

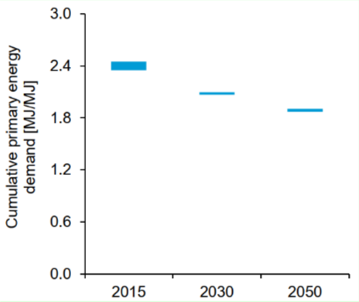
CO2-Capturing	9
Electrolysis	8
Synthesis	7

Life cycle assessment

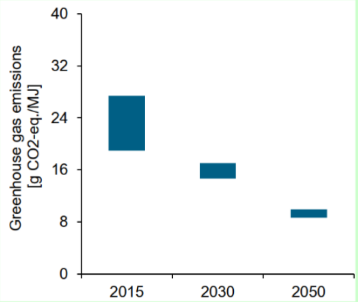
Main contributions
- Electricity for H_2
- CO_2-plant
- Product transport
- PtX-plant

Others include H_2-plant, Auxiliaries, Energie O_2+water, Energy for CO_2

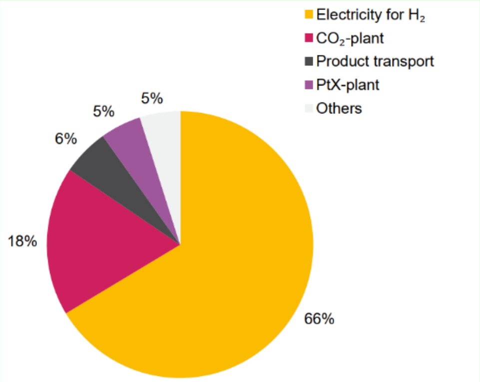
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

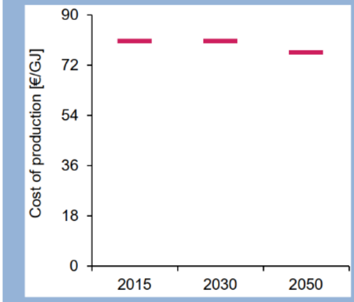


Estimated Cost

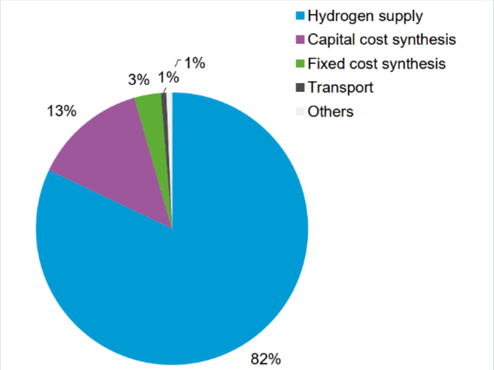
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Fixed cost synthesis
- Transport

Others include Operating materials

Cost of production



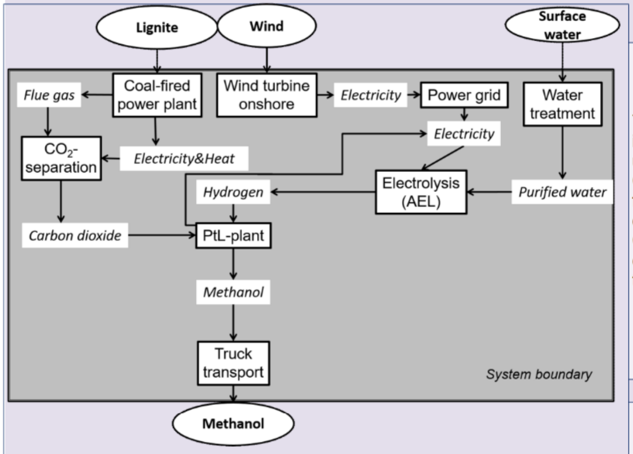
Cost contribution 2015



Stand 18.02.2020

41_Methanol/PtL/WindON/AEL/Lignite Power Plant/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a lignite-fired power plant using electricity from PV. Electricity and heat from the lignite-fired power plant are used otherwise.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

TRL-Level

CO2-Capturing	9
Electrolysis	9
Synthesis	7

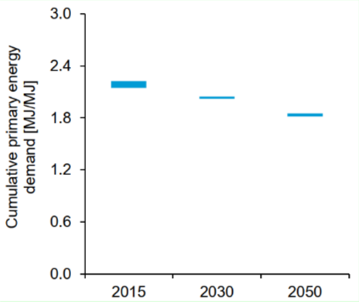
Life cycle assessment

Main contributions

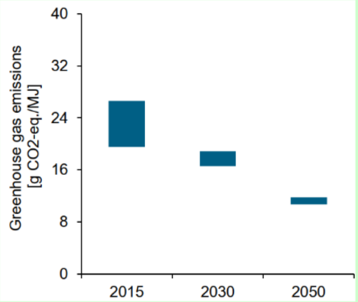
Electricity for H_2
Energy for CO_2
Auxiliaries
Product transport

Others include PtX-plant, H_2-plant, CO_2-plant, Energie O_2+water

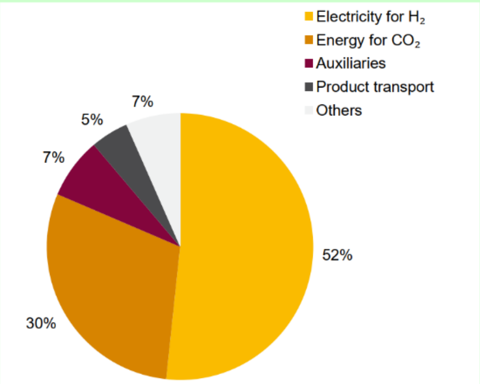
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



Estimated Cost

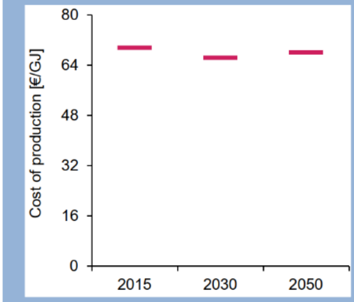
Main contributions

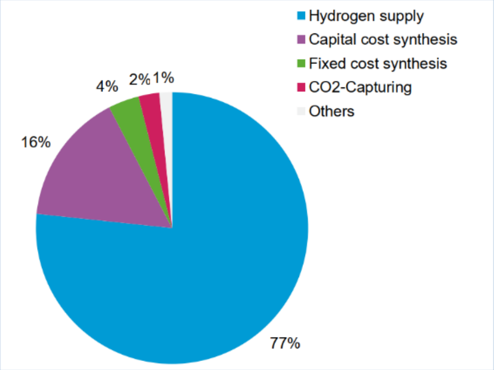
Hydrogen supply
Capital cost synthesis
Fixed cost synthesis
CO2-Capturing

Others include Transport, Operating materials

Cost contribution 2015

Cost of production





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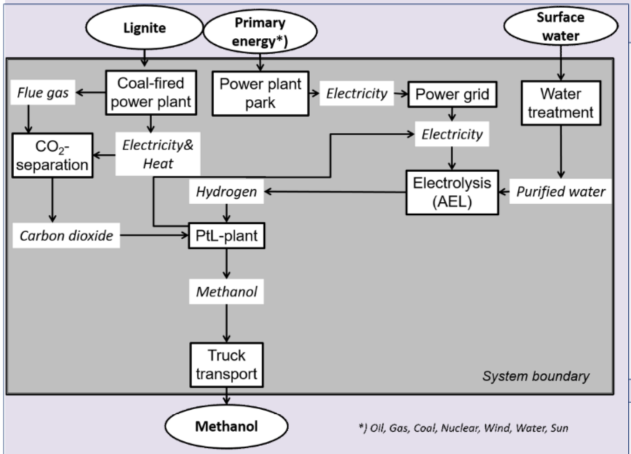
42_Methanol/PtL/Grid Mix/AEL/Lignite Power Plant/Truck_D

Supply path



Description

The electricity is obtained from the electricity mix in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a lignite-fired power plant using electricity from PV. Electricity and heat from the lignite-fired power plant are used otherwise.
CO2 and hydrogen are used in the PtL plant to produce methanol. Excess electricity is used in electrolysis. The methanol is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	90
Efficiency	84%
Investment cost [Mio. €]	325

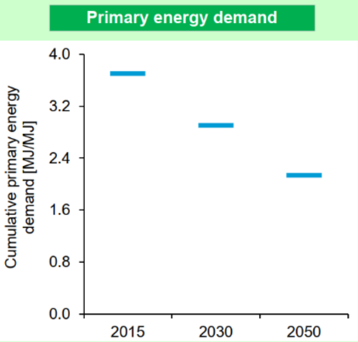
TRL-Level

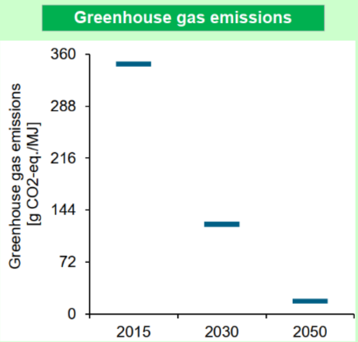
CO2-Capturing	9
Electrolysis	9
Synthesis	7

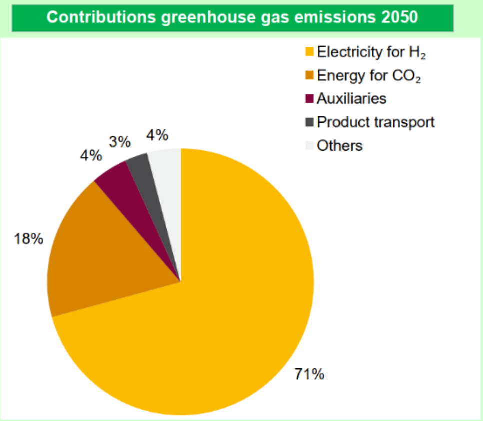
Life cycle assessment

Main contributions
Electricity for H_2
Energy for CO_2
Auxiliaries
Product transport

Others include PtX-plant, H_2-plant, CO_2-plant, Energie O_2+water


Primary energy demand

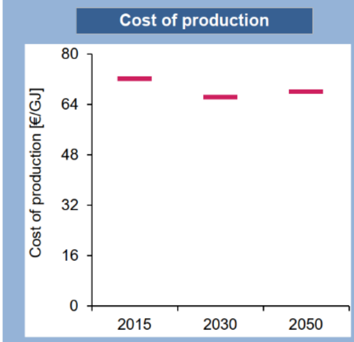

Greenhouse gas emissions

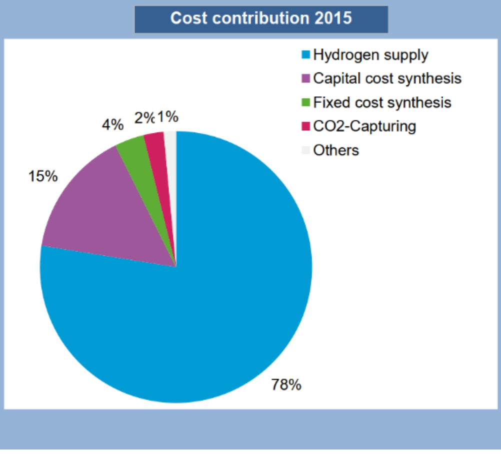

Contributions greenhouse gas emissions 2050

Estimated Cost

Main contributions
Hydrogen supply
Capital cost synthesis
Fixed cost synthesis
CO2-Capturing

Others include Transport, Operating materials


Cost of production


Cost contribution 2015

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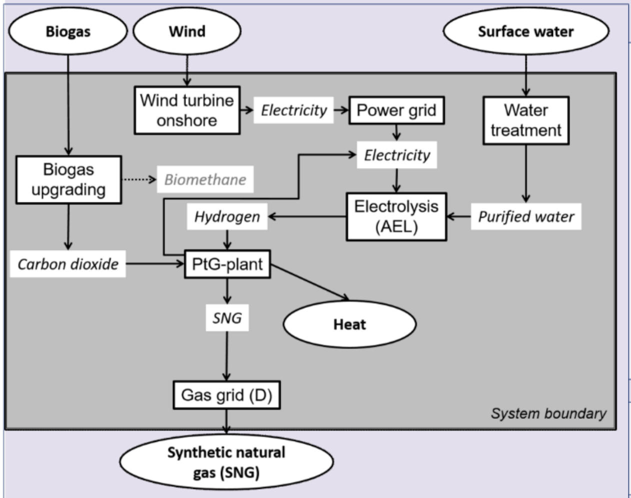
43_SNG/PtG/WindON/AEL/Biogas/Gas Grid (D)_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 from an existing biogas upgrading plant is used.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess electricity generated is used in electrolysis. Excess heat is used otherwise.
The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

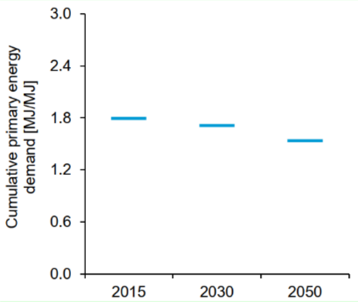
CO2-Capturing	9
Electrolysis	9
Synthesis	7

Life cycle assessment

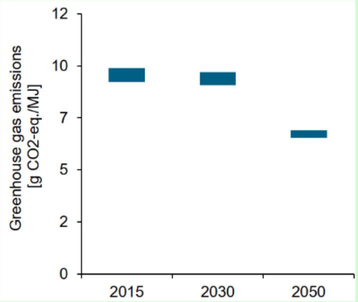
Main contributions	**Others include**
Electricity for H_2 CO_2-plant Auxiliaries H_2-plant	Product transport, Energy for CO_2, PtX-plant, Energie O_2+water

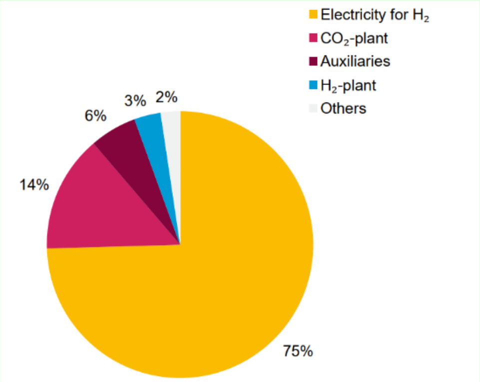
Contributions greenhouse gas emissions 2050

Primary energy demand



Greenhouse gas emissions



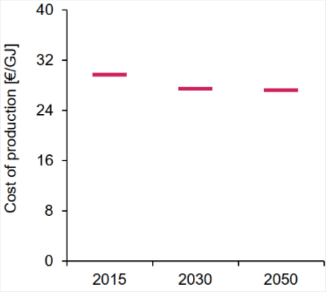


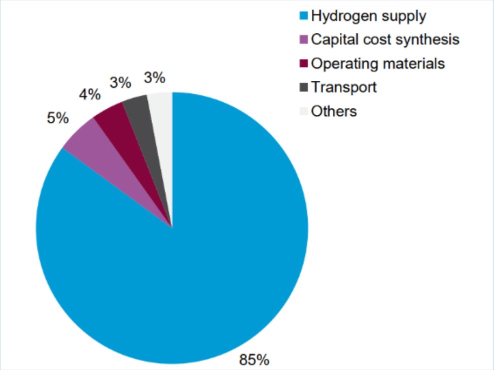
Estimated Cost

Main contributions	**Others include**
Hydrogen supply Capital cost synthesis Operating materials Transport	Fixed cost synthesis, Auxiliary energy

Cost contribution 2015

Cost of production





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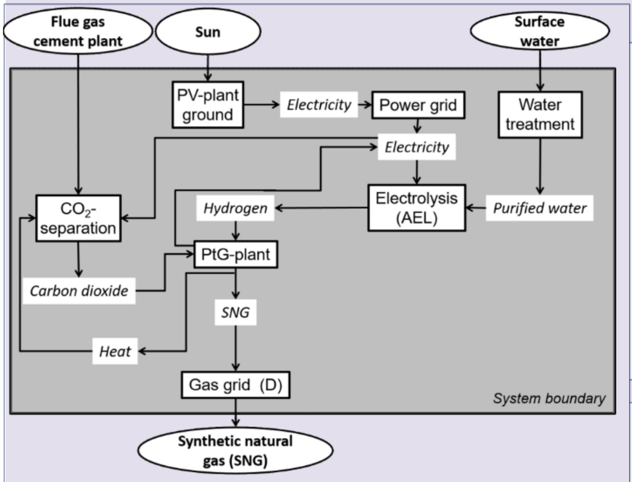
44_SNG/PtG/PVground/AEL/Cement/Gas Grid (D)_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used for the CO2 capture. Excess electricity is used for electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

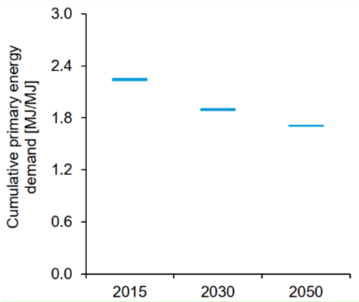
CO2-Capturing	8
Electrolysis	9
Synthesis	7

Life cycle assessment

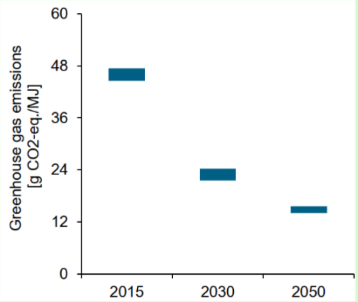
Main contributions
Electricity for H_2
Auxiliaries
H_2-plant
Energy for CO_2

Others include Product transport, PtX-plant, Energie O_2+water, CO_2-plant

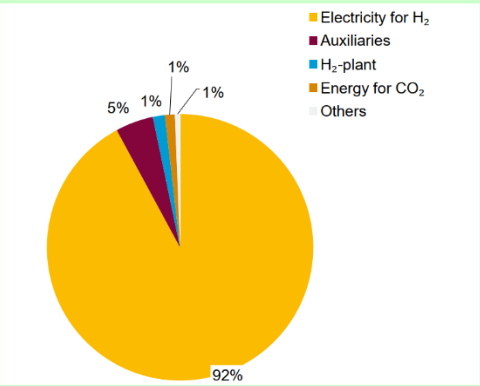
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



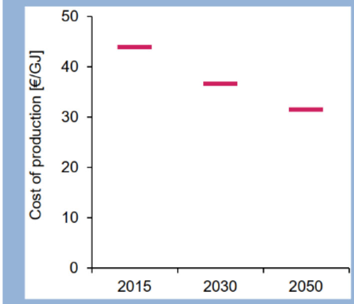
Estimated Cost

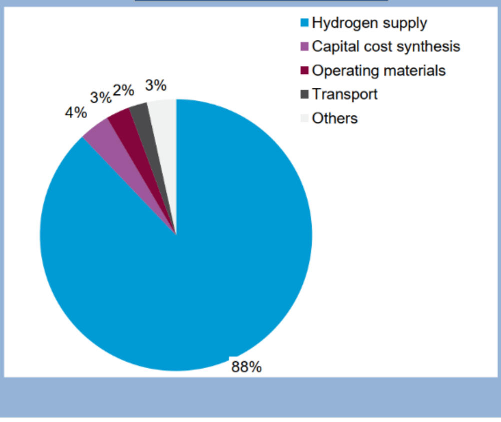
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Transport

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost contribution 2015

Cost of production





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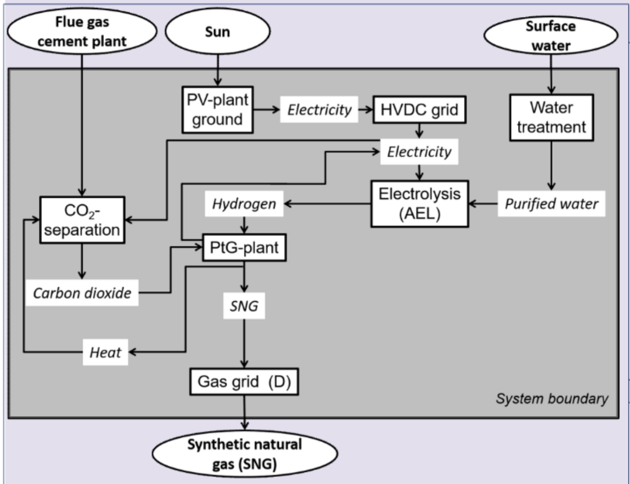
45_SNG/PtG/PVground/AEL/Cement/HVDC+Gas Grid_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and is transferred to the alkaline electrolysis in Germany via the HVDC grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in CO2 capture. Excess electricity is used in electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

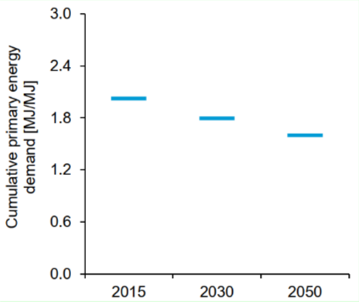
CO2-Capturing	8
Electrolysis	9
Synthesis	7

Life cycle assessment

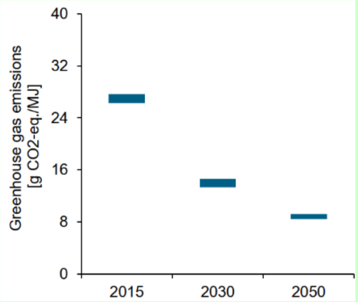
Main contributions
Electricity for H_2
Auxiliaries
Stromtransport HVDC
H_2-plant

Others include Energy for CO_2, Product transport, PtX-plant, Energie O_2+water, CO_2-plant

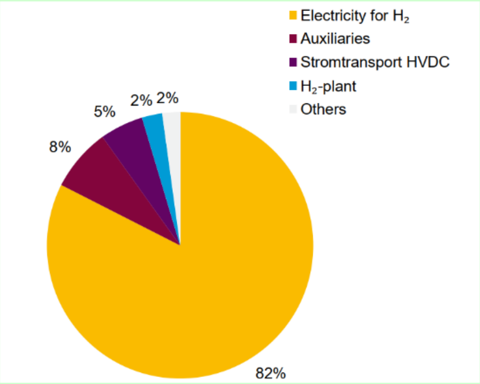
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

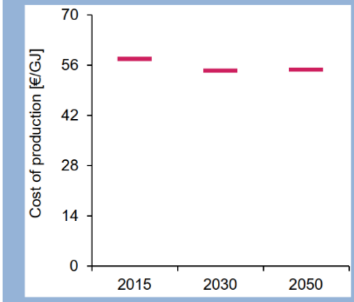


Estimated Cost

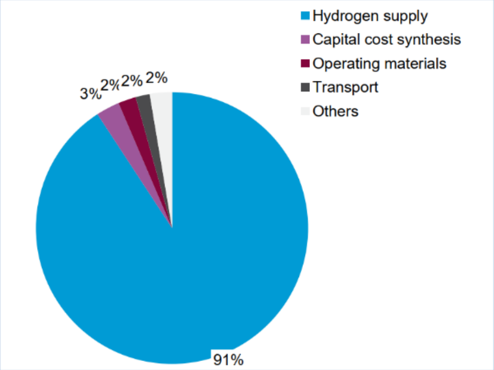
Main contributions
Hydrogen supply
Capital cost synthesis
Operating materials
Transport

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost of production



Cost contribution 2015



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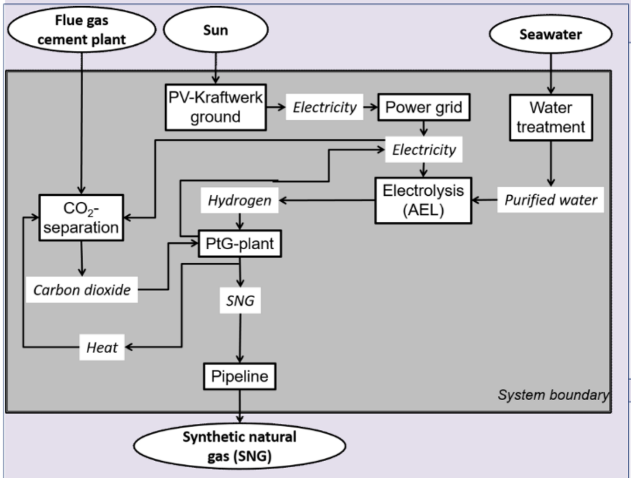
46_SNG/PtG/PVground/AEL/Cement/Pipeline_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas of a cement factory using electricity from PV. CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in CO2 capture. Excess electricity is used in electrolysis. The SNG is fed into a pipeline and transported to Germany.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	7

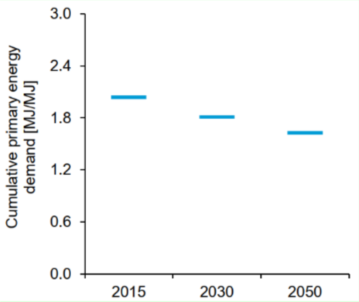
Life cycle assessment

Main contributions

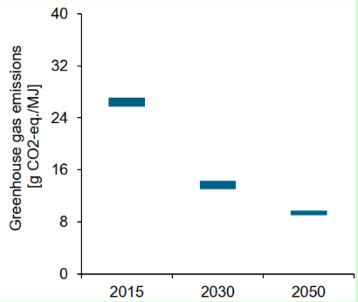
- Electricity for H_2
- Product transport
- Auxiliaries
- H_2-plant

Others include Energy for CO_2, PtX-plant, Energie O_2+water, CO_2-plant

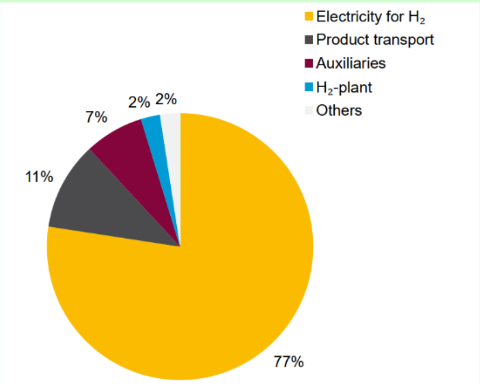
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



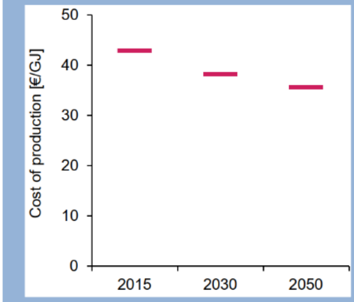
Estimated Cost

Main contributions

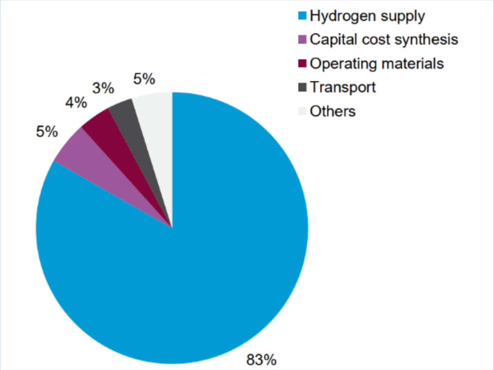
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Transport

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost of production



Cost contribution 2015



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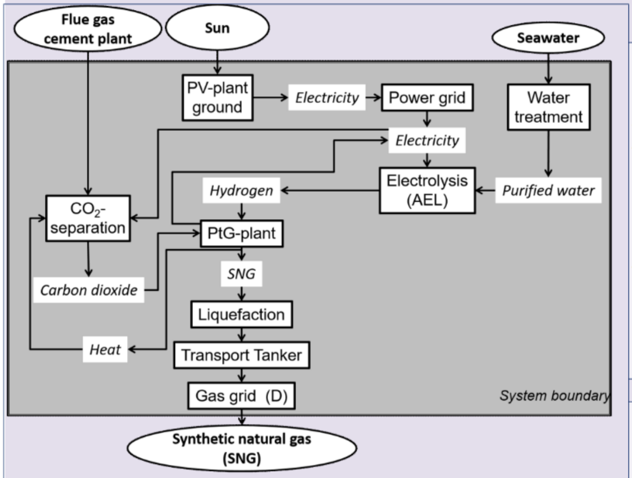
47_SNG/PtG/PVground/AEL/Cement/Tanker+Gas Grid_Saudi Arabia

Supply path



Description

The electricity is generated by ground mounted PV in Saudi Arabia and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis to produce hydrogen.
CO2 is captured from flue gas from a cement factory using electricity from PV. CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in CO2 capture. Excess lectricity generated is used in electrolysis. The SNG is liquefied, brought to Germany in a tanker, fed into the gas grid on site and transported further for use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

CO2-Capturing	8
Electrolysis	9
Synthesis	7

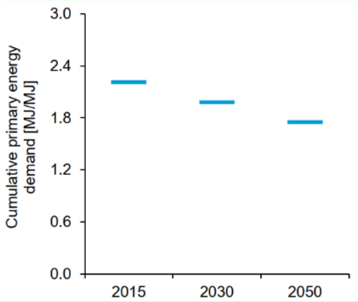
Life cycle assessment

Main contributions

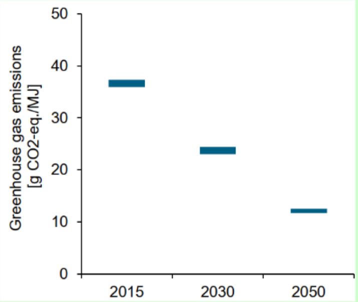
- Electricity for H_2
- Product transport
- Auxiliaries
- H_2-plant

Others include Energy for CO_2, PtX-plant, Energie O_2+water, CO_2-plant

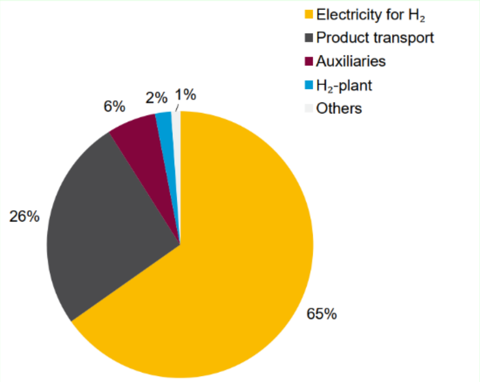
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



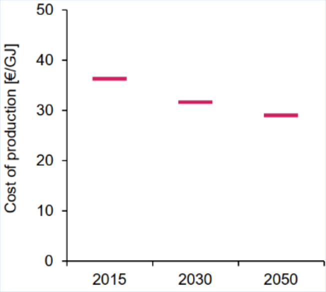
Estimated Cost

Main contributions

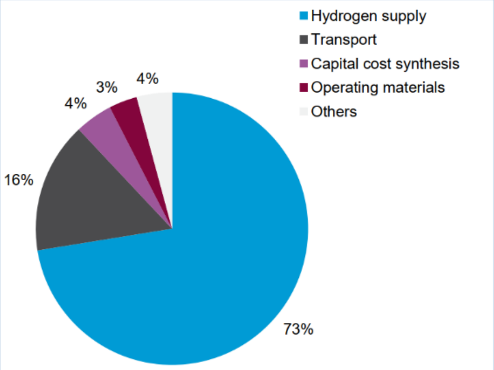
- Hydrogen supply
- Transport
- Capital cost synthesis
- Operating materials

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost of production



Cost contribution 2015



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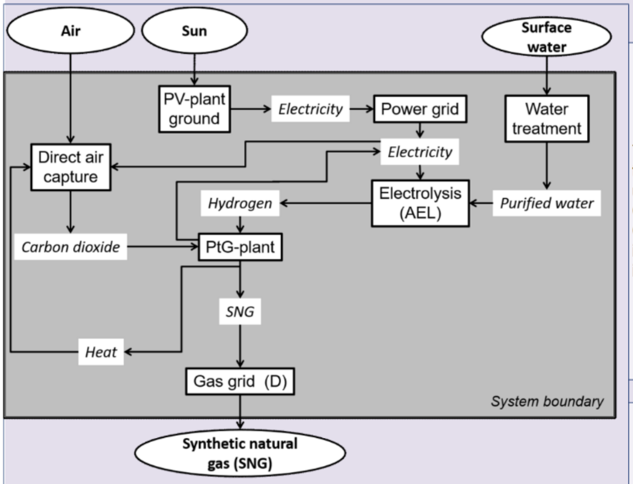
48_SNG/PtG/PVground/AEL/DAC/Gas Grid (D)_D

Supply path



Description

The electricity is generated by ground mounted PV in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from PV.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

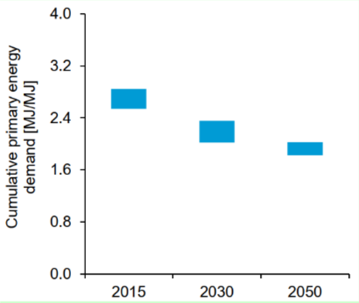
Life cycle assessment

Main contributions

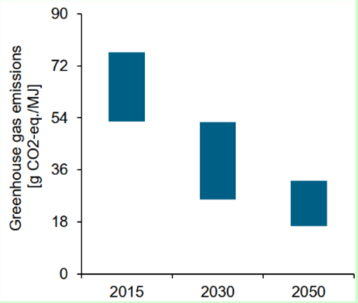
- Electricity for H_2
- CO_2-plant
- Energy for CO_2
- Auxiliaries

Others include H_2-plant, Product transport, PtX-plant, Energie O_2+water

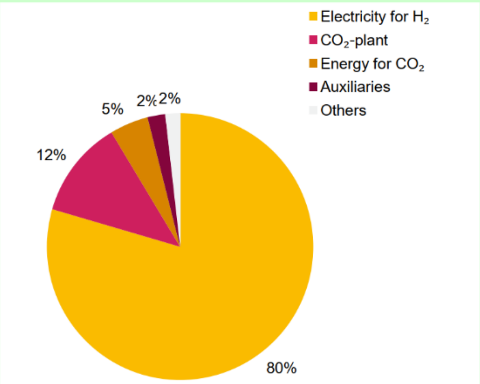
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



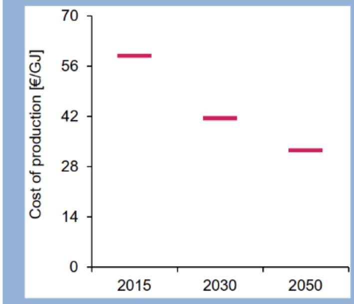
Estimated Cost

Main contributions

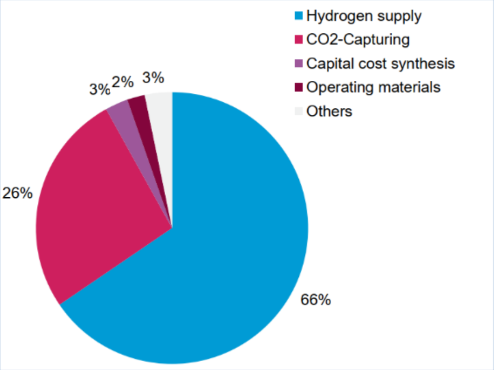
- Hydrogen supply
- CO2-Capturing
- Capital cost synthesis
- Operating materials

Others include Transport, Fixed cost synthesis, Auxiliary energy

Cost of production



Cost contribution 2015



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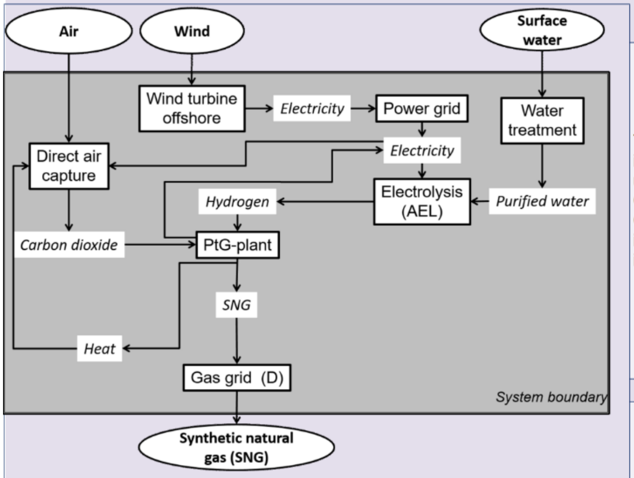
49_SNG/PtG/WindOFF/AEL/DAC/Gas Grid (D)_D

Supply path



Description

The electricity is generated by a offshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from wind power.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

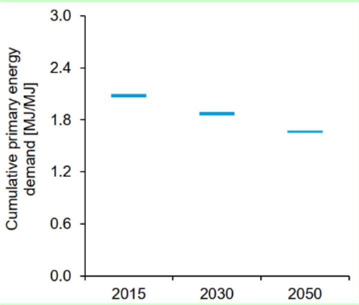
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

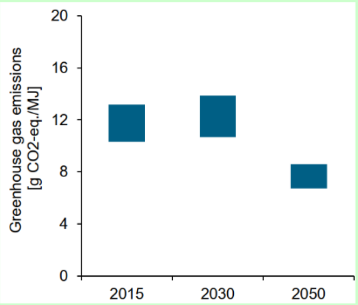
Main contributions
- Electricity for H_2
- CO_2-plant
- Auxiliaries
- Energy for CO_2

Others include H_2-plant, Product transport, PtX-plant, Energie O_2+water

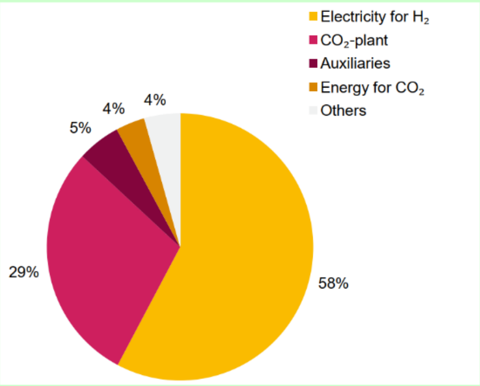
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

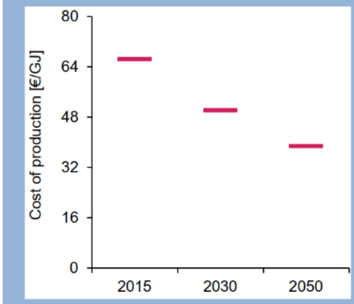


Estimated Cost

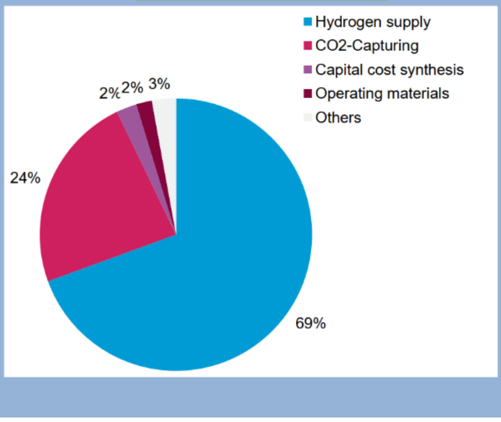
Main contributions
- Hydrogen supply
- CO2-Capturing
- Capital cost synthesis
- Operating materials

Others include Transport, Fixed cost synthesis, Auxiliary energy

Cost of production



Cost contribution 2015



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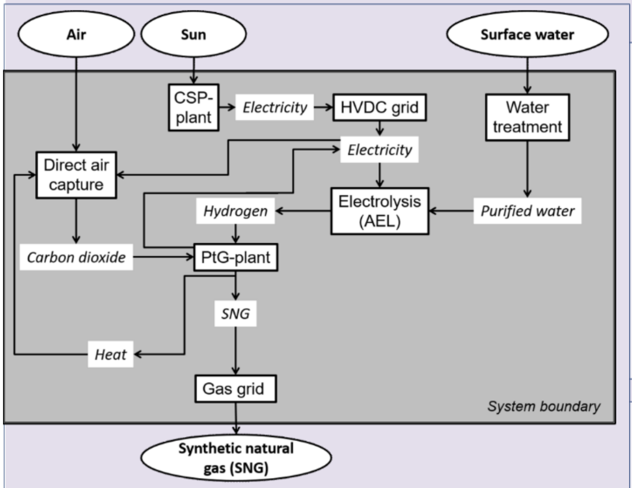
50_SNG/PtG/CSP/AEL/DAC/HVDC+Gas Grid_Morocco

Supply path



Description

The electricity is generated by a CSP power plant in Morocco and is transferred to the alkaline electrolysis plant in Germany via the HVDC transmission grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in the DAC. Excess electricity is used in the electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

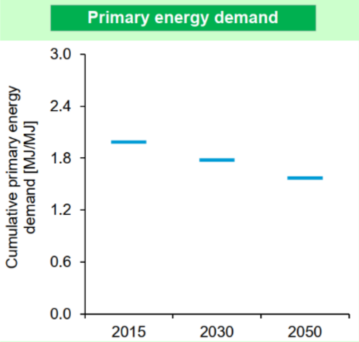
TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

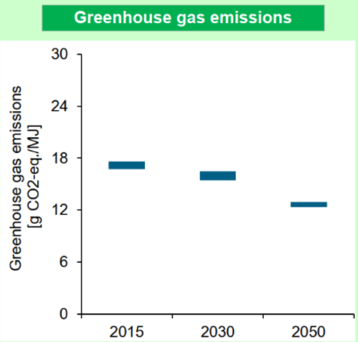
Life cycle assessment

Main contributions	Electricity for H_2 CO_2-plant Energy for CO_2 Auxiliaries	**Others include**	Stromtransport HVDC, H_2-plant, Product transport, Energie O_2+water, PtX-plant

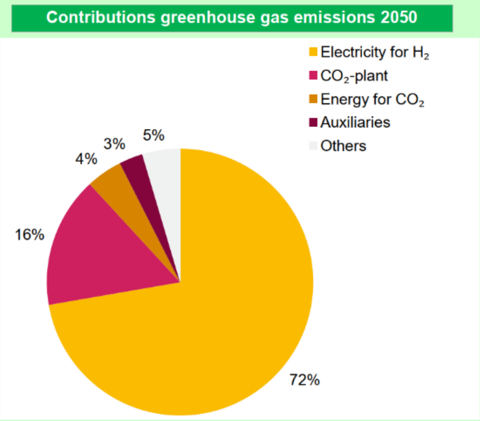
Primary energy demand



Greenhouse gas emissions



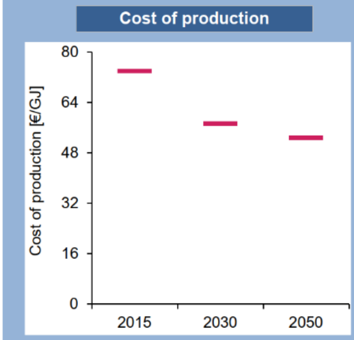
Contributions greenhouse gas emissions 2050



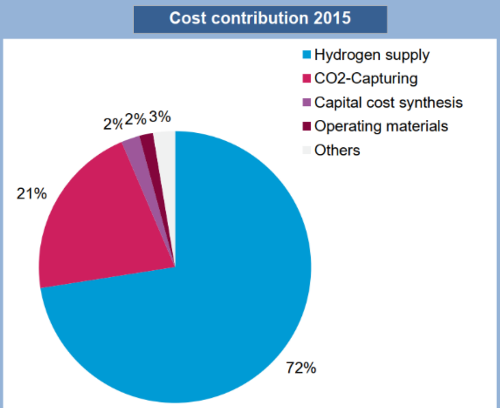
Estimated Cost

Main contributions	Hydrogen supply CO2-Capturing Capital cost synthesis Operating materials	**Others include**	Transport, Fixed cost synthesis, Auxiliary energy

Cost of production



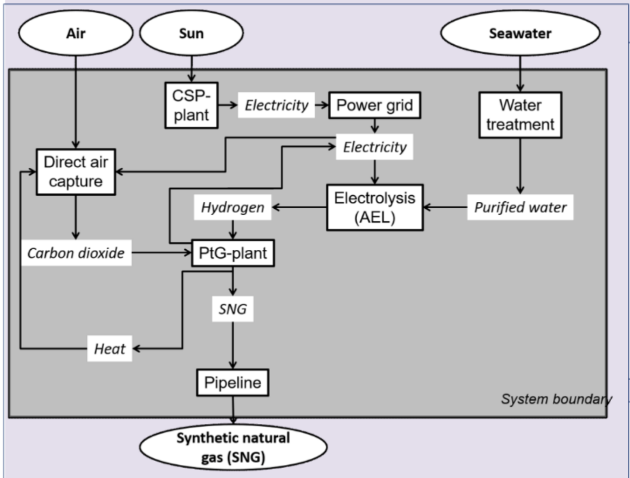
Cost contribution 2015



Stand 18.02.2020

51_SNG/PtG/CSP/AEL/DAC/Pipeline_Morocco

Supply path



Description

The electricity will be generated by a CSP power plant in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis process to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The SNG is fed into the pipeline and transported to Germany.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

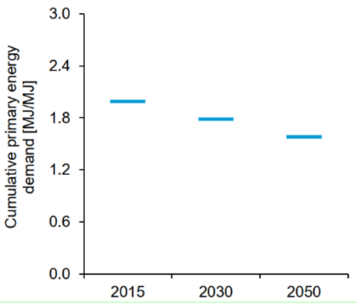
CO2-Capturing	7
Electrolysis	9
Synthesis	7

Life cycle assessment

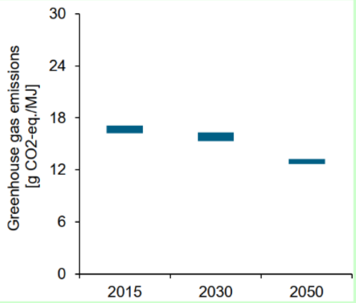
Main contributions
Electricity for H_2
CO_2-plant
Energy for CO_2
Product transport

Others include Auxiliaries, H_2-plant, Energie O_2+water, PtX-plant

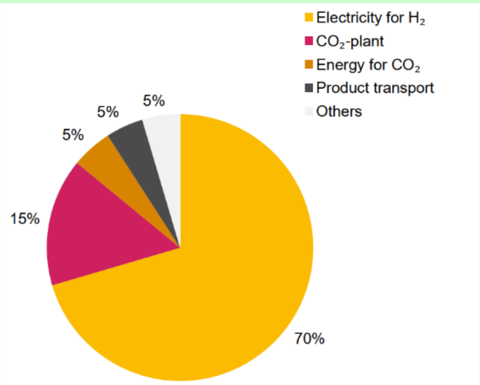
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

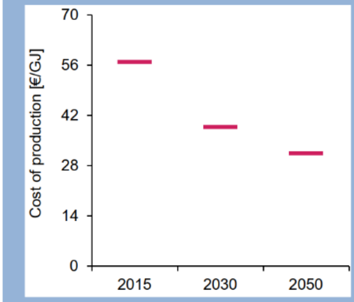


Estimated Cost

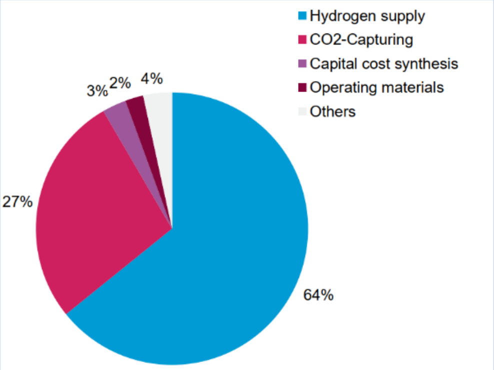
Main contributions
Hydrogen supply
CO2-Capturing
Capital cost synthesis
Operating materials

Others include Transport, Fixed cost synthesis, Auxiliary energy

Cost of production



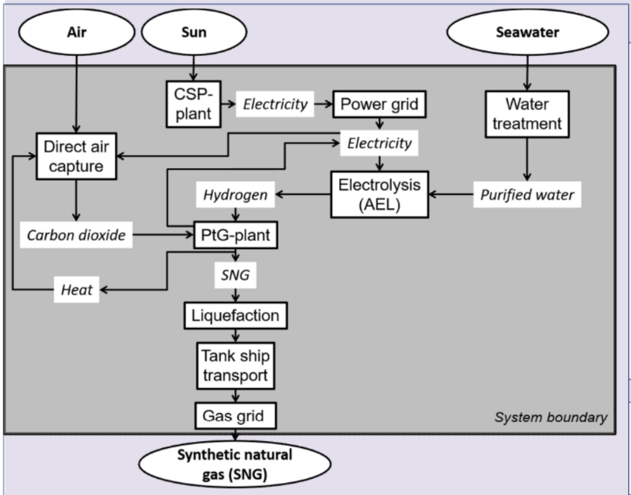
Cost contribution 2015



Stand 18.02.2020

52_SNG/PtG/CSP/AEL/DAC/Tanker+Gas Grid_Morocco

Supply path



Description

The electricity is generated by a CSP power plant in Morocco and is transferred to the alkaline electrolysis via the power grid. Seawater is used in the electrolysis process to produce hydrogen.
CO2 is captured from the air (DAC) using electricity from the CSP power plant.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess heat is used in the DAC. Excess electricity is used in electrolysis. The SNG is liquefied, transported to Germany in a tanker, fed into the gas grid on site and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

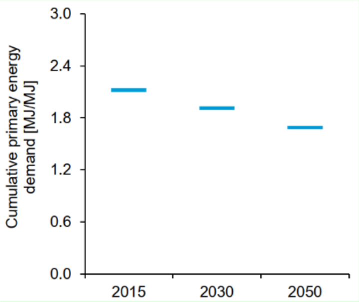
TRL-Level

CO2-Capturing	7
Electrolysis	9
Synthesis	7

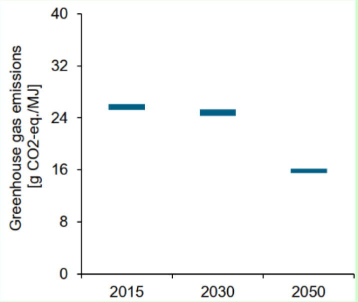
Life cycle assessment

Main contributions		**Others include**
	Electricity for H_2 Product transport CO_2-plant Energy for CO_2	Auxiliaries, H_2-plant, Energie O_2+water, PtX-plant

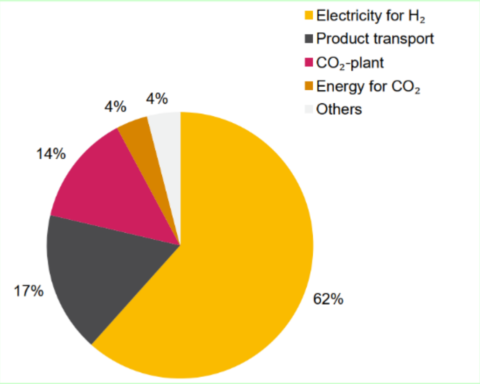
Primary energy demand



Greenhouse gas emissions



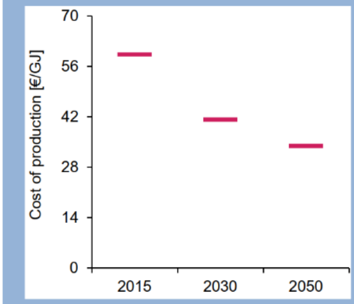
Contributions greenhouse gas emissions 2050



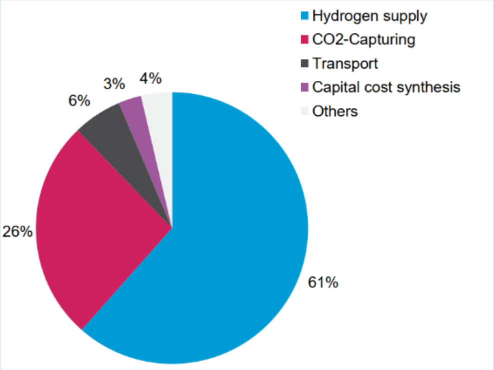
Estimated Cost

Main contributions		**Others include**
	Hydrogen supply CO2-Capturing Transport Capital cost synthesis	Operating materials, Fixed cost synthesis, Auxiliary energy

Cost of production



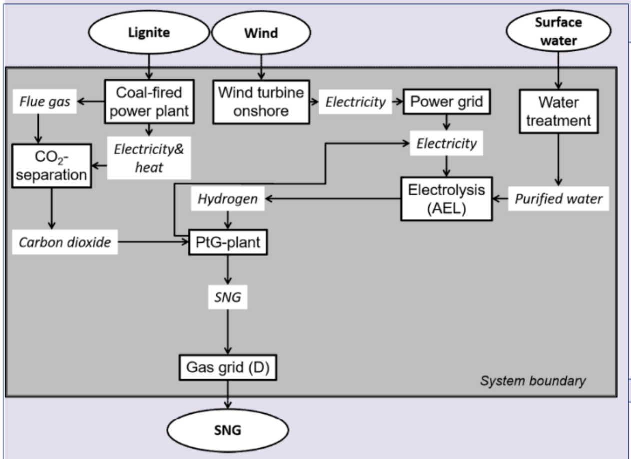
Cost contribution 2015



Stand 18.02.2020

53_SNG/PtG/WindON/AEL/Lignite Power Plant/Gas Grid (D)_D

Supply path



Description

The electricity is generated by an onshore wind power plant in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the flue gas of a lignite-fired power plant. Electricity and heat from the lignite-fired power plant are used otherwise.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess electricity is used in the electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

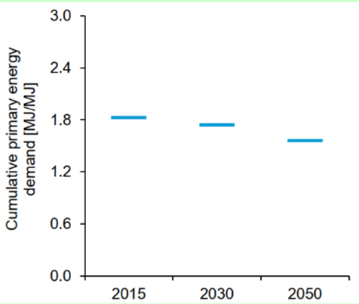
CO2-Capturing	9
Electrolysis	9
Synthesis	7

Life cycle assessment

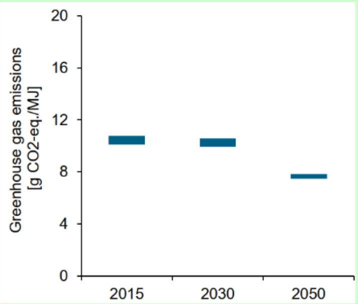
Main contributions
- Electricity for H_2
- Energy for CO_2
- Auxiliaries
- H_2-plant

Others include Product transport, CO_2-plant, PtX-plant, Energie O_2+water

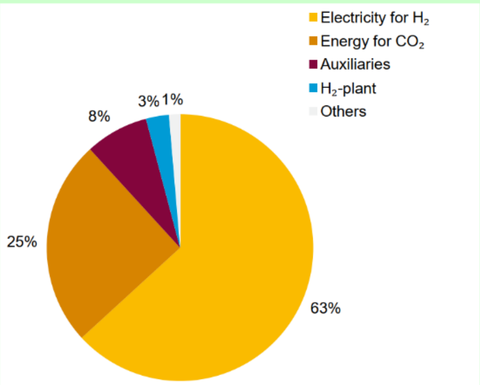
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

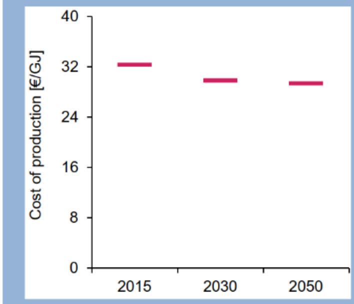


Estimated Cost

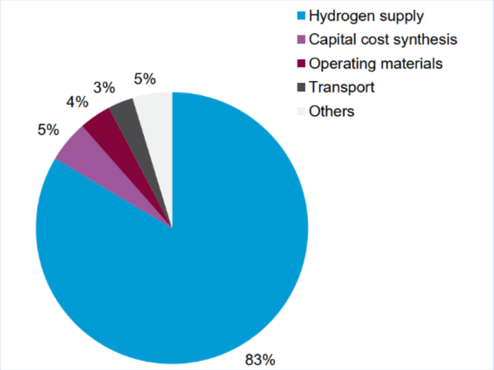
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Transport

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost of production



Cost contribution 2015



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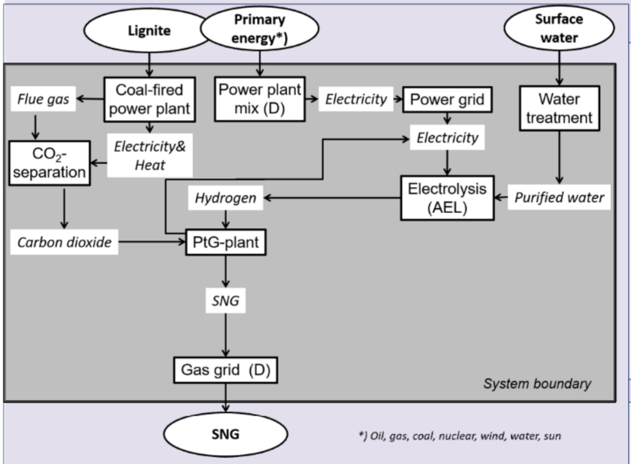
54_SNG/PtG/Grid Mix/AEL/Lignite Power Plant/Gas Grid (D)_D

Supply path



Description

The electricity is obtained from the electricity mix in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the flue gas of a lignite-fired power plant. Electricity and heat from the lignite-fired power plant are used otherwise.
CO2 and hydrogen are used in the PtG plant to produce SNG. Excess electricity is used in electrolysis. The SNG is fed into the gas grid and transported for further use.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	6
Efficiency	78%
Investment cost [Mio. €]	3

TRL-Level

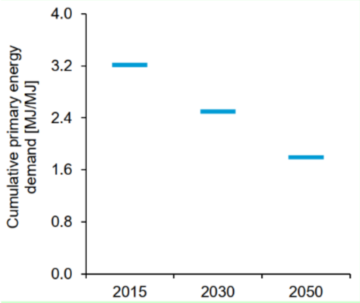
CO2-Capturing	9
Electrolysis	9
Synthesis	7

Life cycle assessment

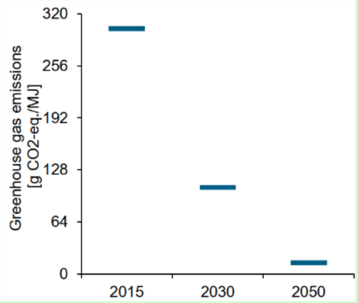
Main contributions
- Electricity for H_2
- Energy for CO_2
- Auxiliaries
- H_2-plant

Others include Product transport, CO_2-plant, PtX-plant, Energie O_2+water

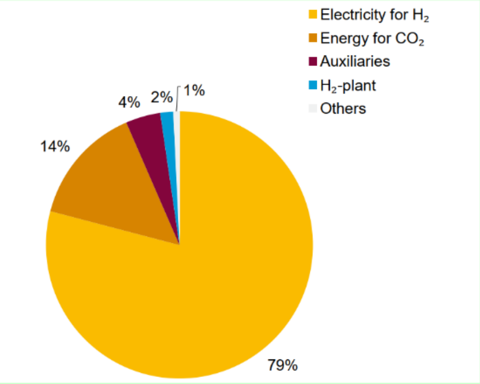
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

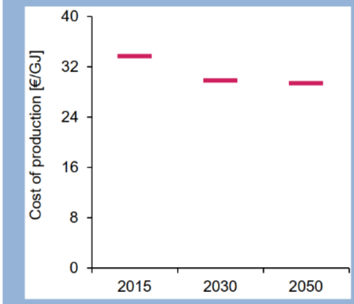


Estimated Cost

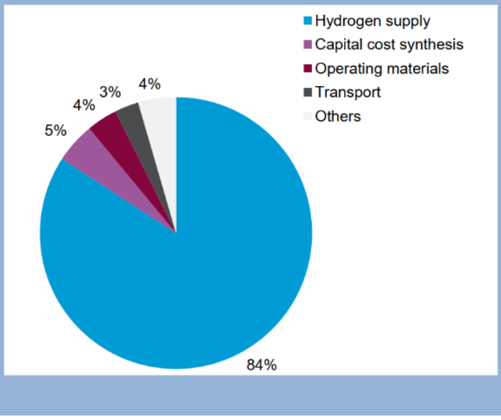
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Transport

Others include Fixed cost synthesis, CO2-Capturing, Auxiliary energy

Cost of production



Cost contribution 2015



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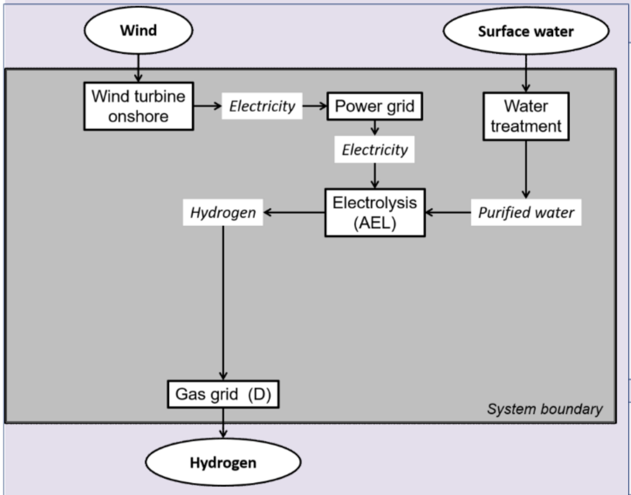
55_H2/H2/WindON/AEL/Gas Grid (D)_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	1
Efficiency	67%
Investment cost [Mio. €]	1

TRL-Level

CO2-Capturing	n.a.
Electrolysis	9
Synthesis	7

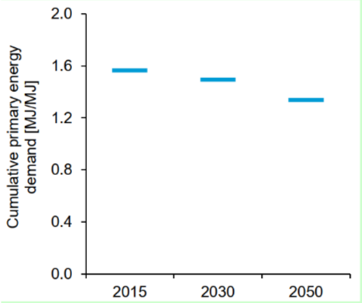
Life cycle assessment

Main contributions

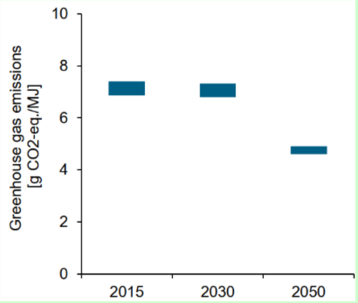
- Electricity for H_2
- Auxiliaries
- H_2-plant
- Energie O_2+water

Others include none

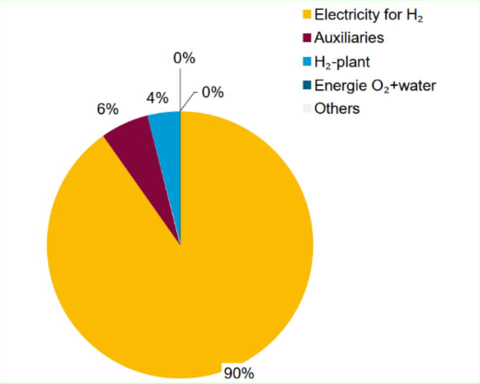
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



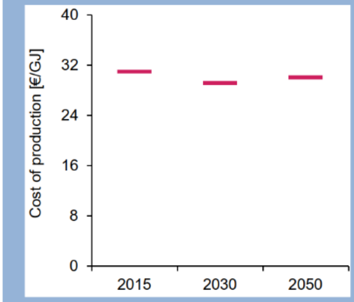
Estimated Cost

Main contributions

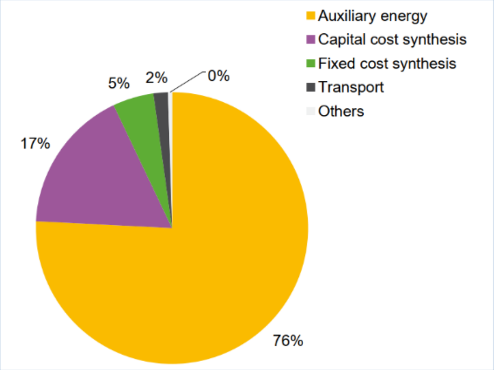
- Auxiliary energy
- Capital cost synthesis
- Fixed cost synthesis
- Transport

Others include Operating materials

Cost of production



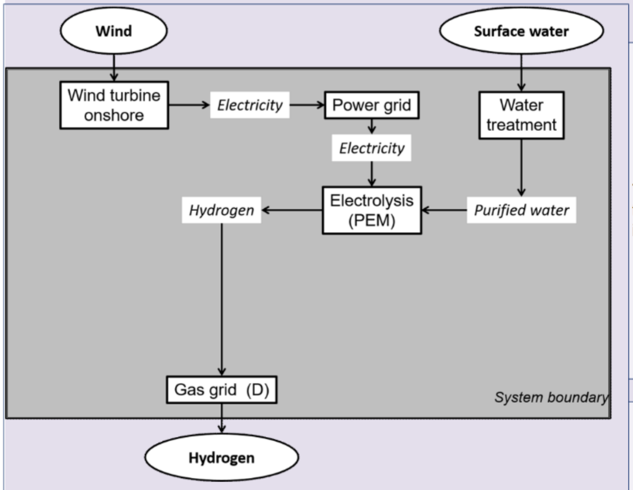
Cost contribution 2015



Stand 18.02.2020

56_H2/H2/WindON/PEM/Gas Grid (D)_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and transported to the PEM electrolysis plant via the power grid. Surface water is used in the electrolysis to produce hydrogen.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	1
Efficiency	67%
Investment cost [Mio. €]	1

TRL-Level

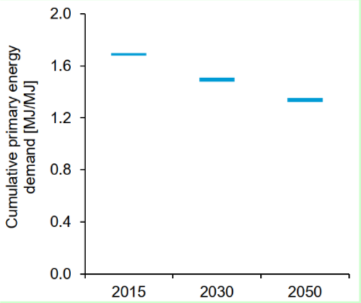
CO2-Capturing	n.a.
Electrolysis	8
Synthesis	7

Life cycle assessment

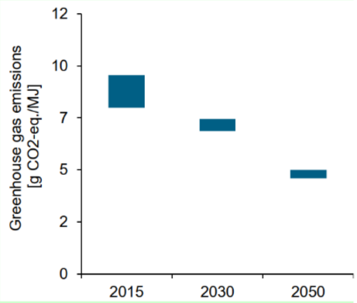
Main contributions
Electricity for H_2
H_2-plant
Auxiliaries
Energie O_2+water

Others include none

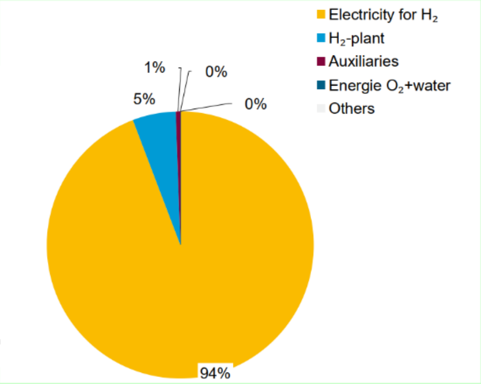
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

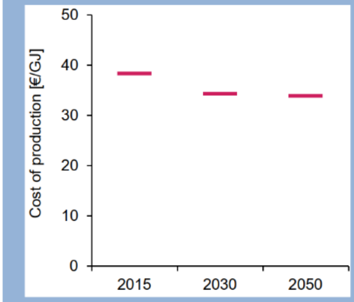


Estimated Cost

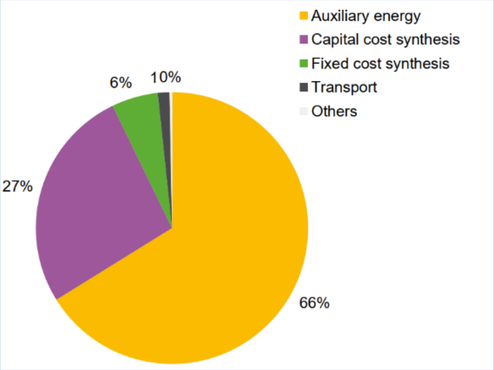
Main contributions
Auxiliary energy
Capital cost synthesis
Fixed cost synthesis
Transport

Others include Operating materials

Cost of production



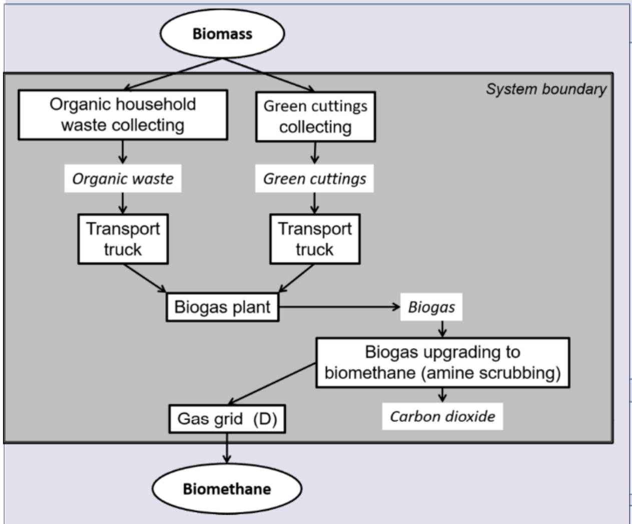
Cost contribution 2015



Stand 18.02.2020

57_Biomethane/Fermentation/Bio Waste/Green Waste/Gas Grid (D)_D

Supply path



Description

Household biowaste and green cuttings are collected in Germany and taken to a biogas plant. The biogas is refined into Biomethanee using amine scrubbing and fed into the gas network.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	7

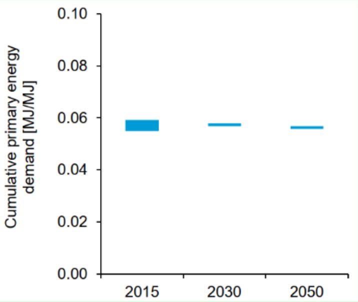
Life cycle assessment

Main contributions

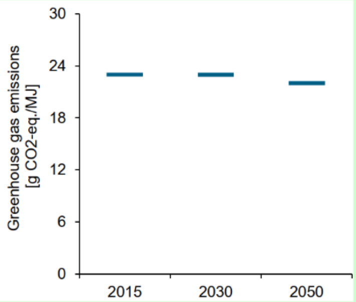
Energy for CO_2
Biogasanlage
CO_2-plant
Biomass supply

Others include Product transport, Auxiliaries

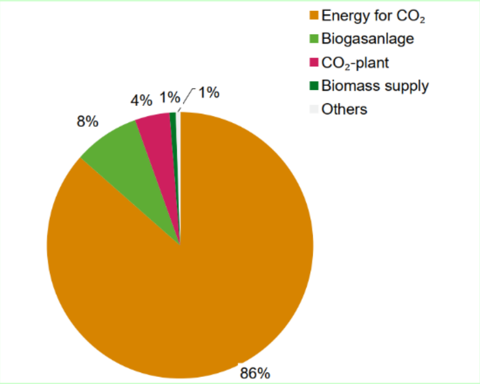
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



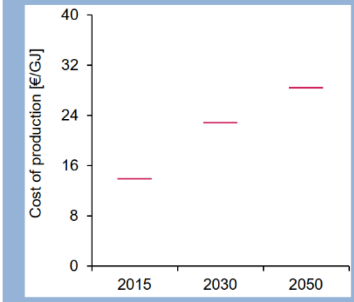
Estimated Cost

Main contributions

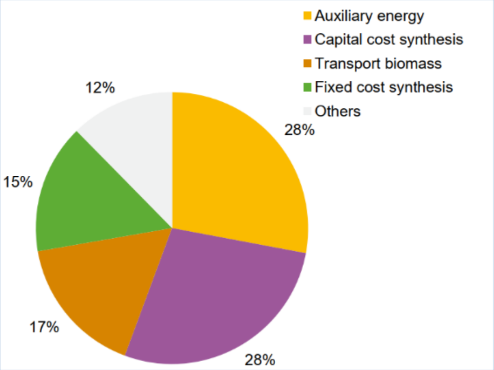
Auxiliary energy
Capital cost synthesis
Transport biomass
Fixed cost synthesis

Others include Transport, Operating materials

Cost of production



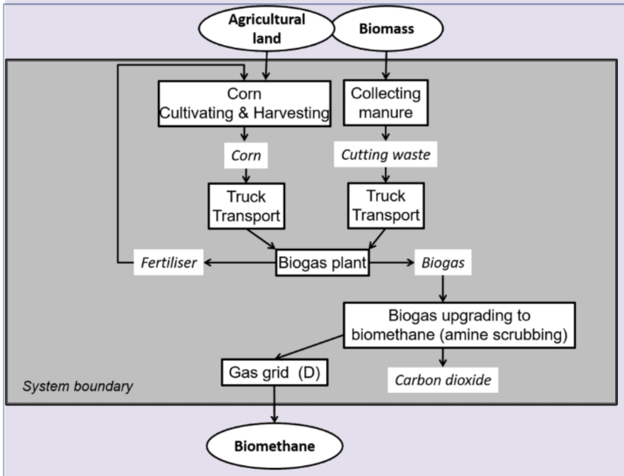
Cost contribution 2015



Stand 18.02.2020

58_Biomethane/Fermentation/Maize/Manure/Gas Grid (D)_D

Supply path



Description

Manure and whole corn plants are brought to a biogas plant in Germany. The biogas is refined into Biomethanee using amine scrubbing and fed into the gas grid.
The fertiliser from the biogas plant is reused for the cultivation of corn.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

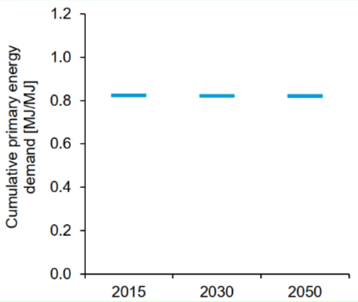
CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	7

Life cycle assessment

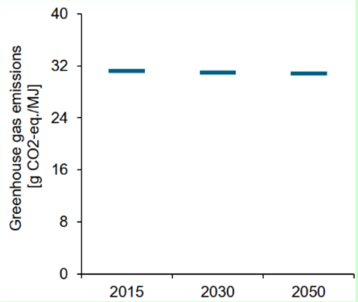
Main contributions
- Energy for CO_2
- Biomass supply
- Biogasanlage
- CO_2-plant

Others include Product transport, Auxiliaries

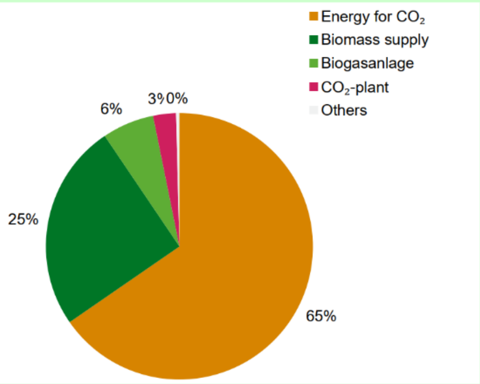
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050

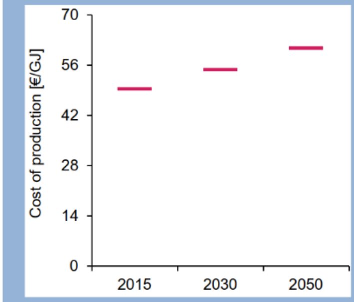


Estimated Cost

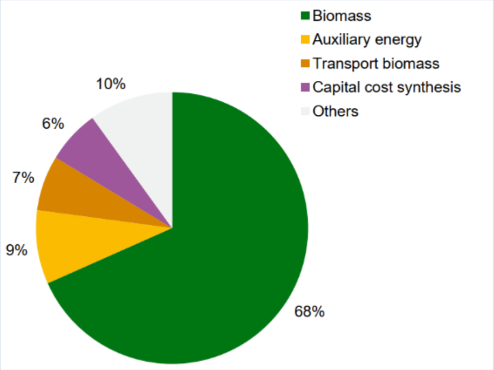
Main contributions
- Biomass
- Auxiliary energy
- Transport biomass
- Capital cost synthesis

Others include Fixed cost synthesis, Transport, Operating materials

Cost of production



Cost contribution 2015



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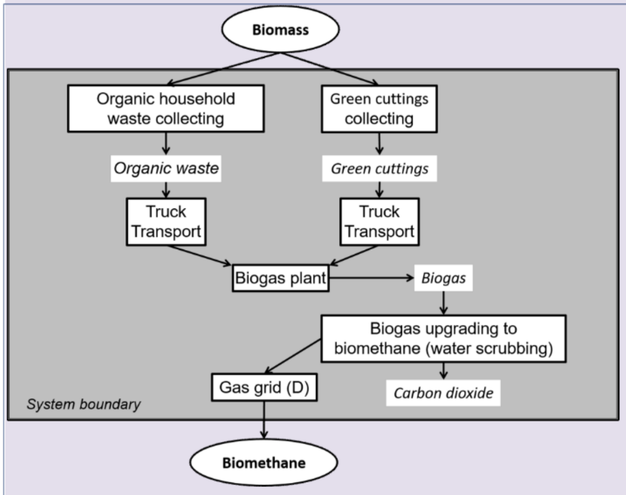
59_Biomethane/Fermentation/Bio Waste/Green Waste/Gas Grid (D)_D

Supply path



Description

Household biowaste and green cuttings are collected in Germany and taken to a biogas plant. The biogas is refined into Biomethanee using water scrubbing and fed into the gas network.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	7

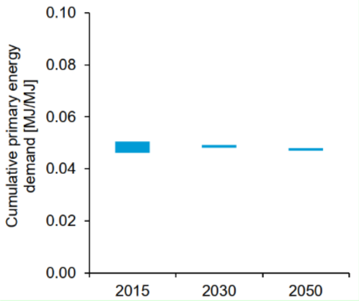
Life cycle assessment

Main contributions

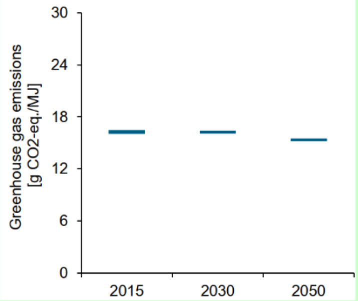
- Energy for CO_2
- Biogasanlage
- CO_2-plant
- Biomass supply

Others include Product transport, Auxiliaries, Energie O_2+water

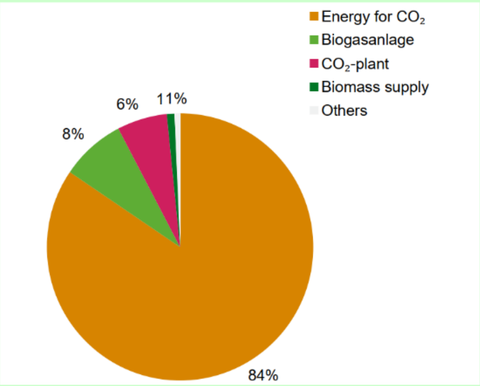
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



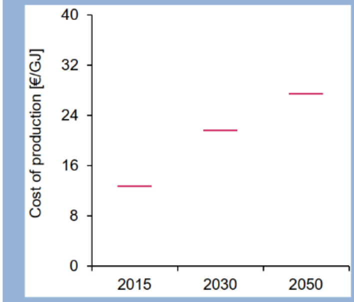
Estimated Cost

Main contributions

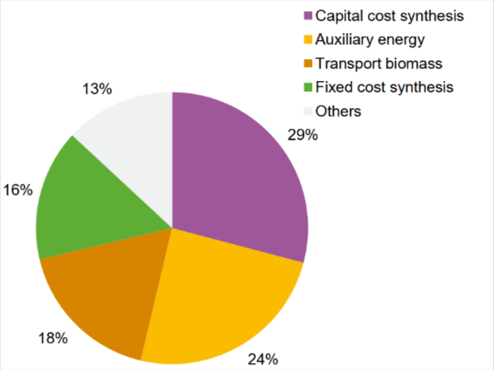
- Capital cost synthesis
- Auxiliary energy
- Transport biomass
- Fixed cost synthesis

Others include Transport, Operating materials

Cost of production



Cost contribution 2015



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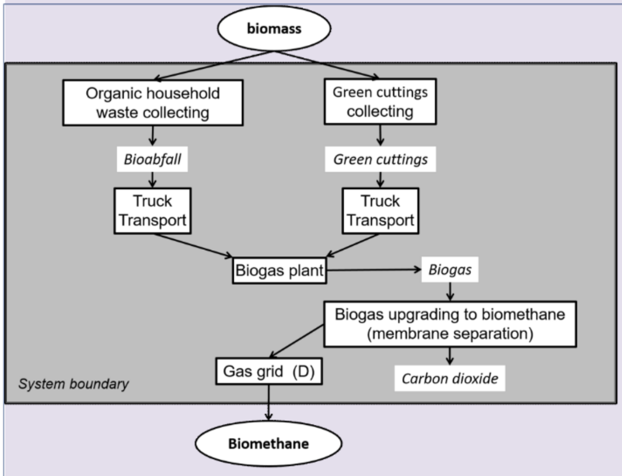
60_Biomethane/Fermentation/Bio Waste/Green Waste/Gas Grid (D)_D

Supply path



Description

Household biowaste and green cuttings are collected in Germany and taken to a biogas plant.The biogas is refined into Biomethanee by means of membrane separation and fed into the gas network.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

CO2-Capturing	n.a.
Electrolysis	n.a.
Synthesis	7

Life cycle assessment

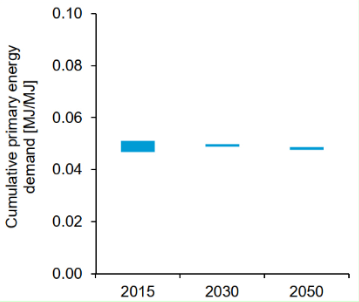
Main contributions

Energy for CO_2
Biogasanlage
CO_2-plant
Biomass supply

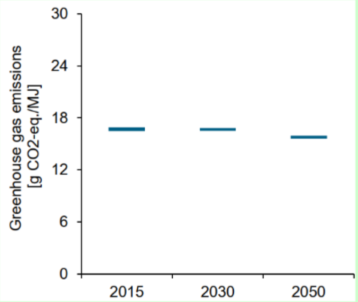
Others include Product transport, Auxiliaries

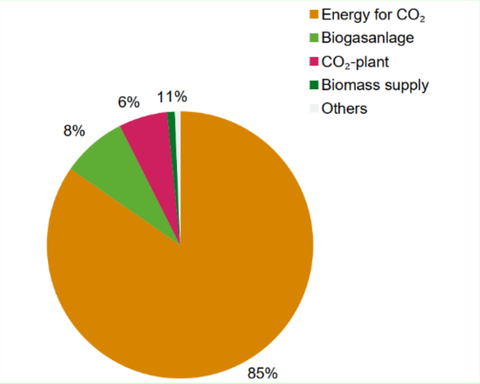
Contributions greenhouse gas emissions 2050

Primary energy demand



Greenhouse gas emissions





Estimated Cost

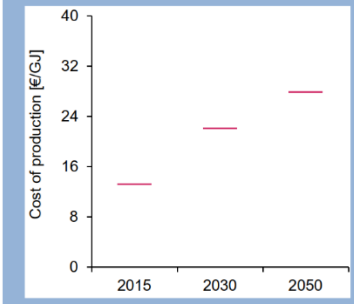
Main contributions

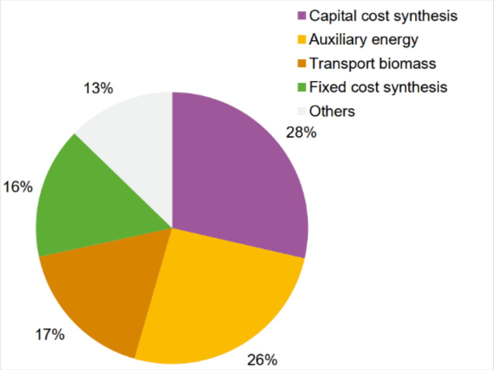
Capital cost synthesis
Auxiliary energy
Transport biomass
Fixed cost synthesis

Others include Transport, Operating materials

Cost contribution 2015

Cost of production





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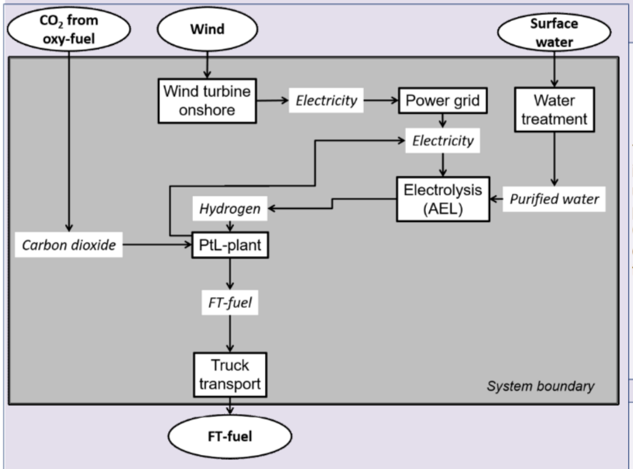
61_PtL/PtL/WindON/Flue Gas Oxyfuel Power Plant/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen. CO2 is taken from the oxyfuel power plant, where the CO2 is already captured for storage (CCS).
CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity is used for electrolysis. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

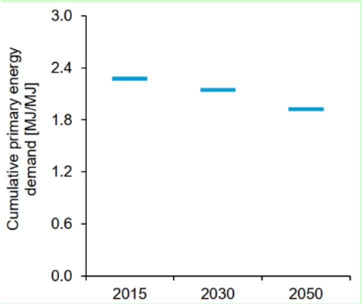
CO2-Capturing	8
Electrolysis	n.a.
Synthesis	7

Life cycle assessment

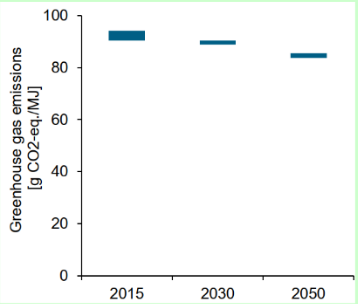
Main contributions
- CO_2 aus Oxyfuel
- Electricity for H_2
- Auxiliaries
- H_2-plant

Others include Product transport, PtX-plant, Energie O_2+water

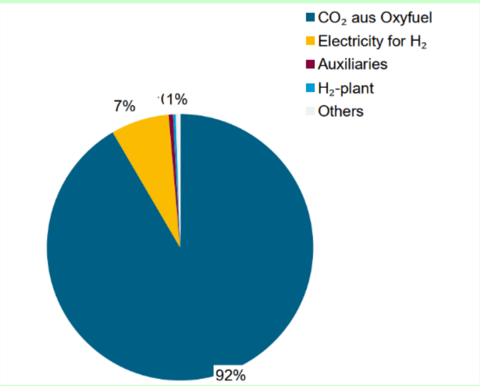
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



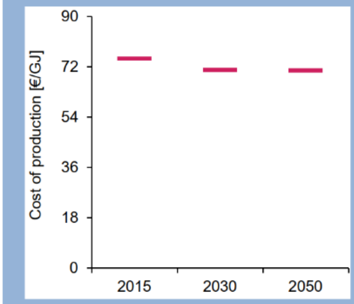
Estimated Cost

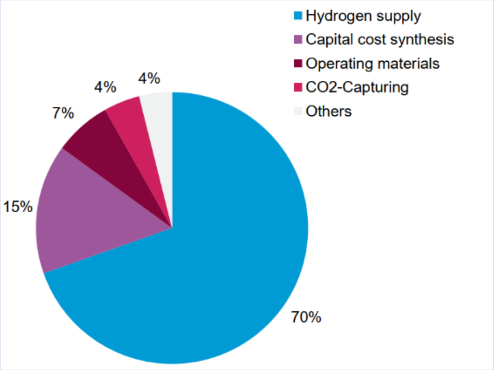
Main contributions
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- CO2-Capturing

Others include Fixed cost synthesis, Transport

Cost contribution 2015

Cost of production





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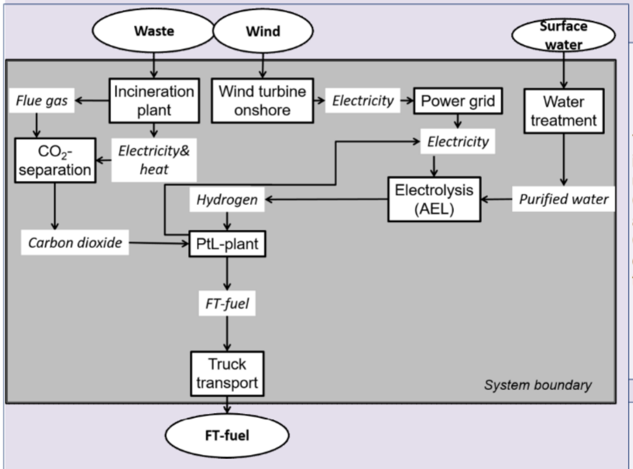
62_PtL/PtL/WindON/Flue Gas WIP (Waste)/Truck_D

Supply path



Description

The electricity is generated by onshore wind power plants in Germany and is transferred to the alkaline electrolysis via the power grid. Surface water is used in the electrolysis to produce hydrogen.
CO2 is captured from the flue gas of a waste incineration plant. Electricity and heat from the plant are used otherwise.
CO2 and hydrogen are used in the PtL plant to produce FT fuel. Excess electricity is used for electrolysis. The FT fuel is stored and distributed via truck.

Parameters for the production of storable energy sources (2015)

Capacity [MW]	n.a.
Efficiency	n.a.
Investment cost [Mio. €]	n.a.

TRL-Level

CO2-Capturing	8
Electrolysis	n.a.
Synthesis	7

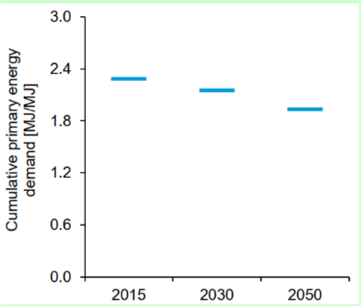
Life cycle assessment

Main contributions

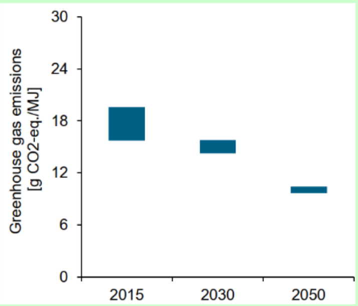
- Electricity for H_2
- Energy for CO_2
- Auxiliaries
- H_2-plant

Others include Product transport, PtX-plant, Energie O_2+water, CO_2-plant

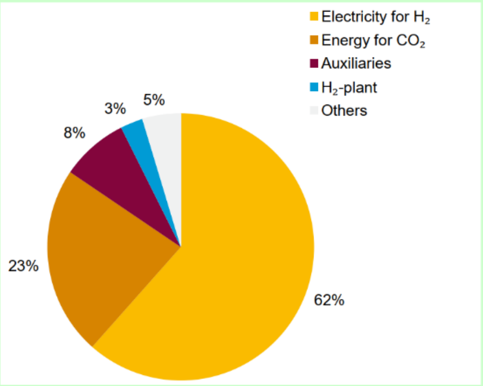
Primary energy demand



Greenhouse gas emissions



Contributions greenhouse gas emissions 2050



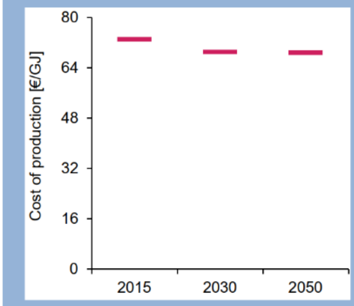
Estimated Cost

Main contributions

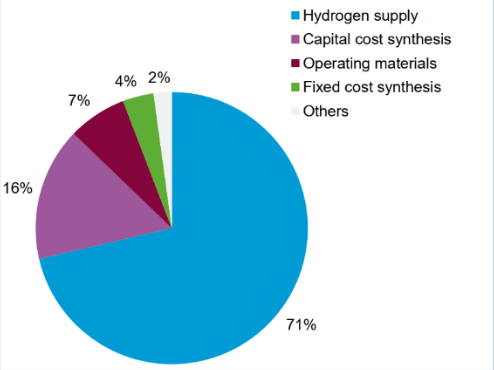
- Hydrogen supply
- Capital cost synthesis
- Operating materials
- Fixed cost synthesis

Others include CO2-Capturing, Transport

Cost of production



Cost contribution 2015



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