

Life Cycle Assessment

Power-to-X



Terminology and abbreviations

AEL	Alkaline water electrolysis
BEV	Battery electric vehicles
CCS	Carbon capture and storage
CED_f	Cumulative fossil energy demand
CO_2 -eq.	Carbon dioxide equivalents
CRD	Cumulative resource demand
CPOX	Catalytic partial oxidation
DAC	Direct air capture: a process to extract CO_2 from the atmosphere
FCEV	Fuel cell electric vehicle
FT	Fischer-Tropsch synthesis
Functional unit	Quantified performance of a product system for use as a reference unit
GHG	Greenhouse gas
GtL	Gas-to-Liquid
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
MEA	Monoethanolamine
MENA	Middle East and Northern Africa
PEM	Proton exchange membrane
PSA	Pressure swing adsorption
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X: synthesis processes providing numerous products using (renewable) electricity
PWS	Pressurized water scrubbing
RWGS	Reverse water gas shift reaction
SNG	Synthetic natural gas
SOEC	Solid oxide electrolyzer cell

Summary

[INERATEC](#), a German tech company, offers modular synthesis units that allow the production of hydrocarbons that can directly replace conventional fossil based, gaseous or liquid fuels, chemicals or waxes. **The synthesis units convert CO₂ and hydrogen to synthetic natural gas (SNG), liquid fuels (naphtha, diesel, gasoline and kerosene), methanol and waxes. These products can readily replace fossil-derived fuels and chemicals using today's infrastructure.** In future, these synthesis units will likely use hydrogen produced by electrolysis. Therefore, these processes are often labelled power-to-X (PtX) processes. High quantities of electricity are needed to produce hydrogen by electrolysis. Many future supply chains located in different countries could thus be viable options to provide electricity to produce the required hydrogen.

In this study, **potential changes in GHG emissions** and changes in **resource demand** of different PtX supply chains are discussed. The study comprises many different supply chains in different locations to supply fuels and waxes (produced by a Fischer-Tropsch (FT) synthesis), methanol or SNG. **The assessment comprises the PtX supply chain product use and displacement of conventional fossil fuels and chemicals.**

PtX products outperform conventional, fossil-based fuels and chemicals by far in terms of GHG emissions, if electricity is provided from renewable sources. It is therefore important to ensure that PtX fuels are produced using renewable energy. **In terms of resource demand, the assessed PtX fuels require more mineral resources than conventional fuels.** This is due to the resource demand for additional infrastructure requirements, i.e. renewable electricity provision. A comparison with other alternatives to fossil fuels shows that in certain sectors, such as the aviation and maritime sectors, there are very few or no viable alternatives in sight that could facilitate a timely reduction of GHG emissions in these sectors.

INERATEC

[INERATEC](#) developed modular and scalable chemical reactors that allow the production of liquid and gaseous hydrocarbons, such as liquid fuels, chemicals and waxes using (surplus) renewable electricity, water and a carbon source (e.g. carbon dioxide (CO₂) or carbon monoxide (CO)). INERATEC offers different reactor configurations that facilitate a variety of synthesis processes, including synthesis gas production (via steam-assisted catalytic partial oxidation (CPOX) or reverse water gas shift (RWGS), Fischer-Tropsch (FT) synthesis and direct methanation of CO₂. These synthesis processes can yield numerous products that can substitute fossil-derived transportation fuels (e.g. substituting kerosene), energy carriers (e.g. natural gas), chemical products (e.g. fossil-derived waxes and oils) and platform chemicals (e.g. fossil-derived methanol). A carbon source, such as CO₂ from biogas, direct air capture (DAC), obtained from combustion processes (biogenic or fossil energy carriers) as well as industrial processes, such as CO₂ captured in the cement industry, is required. In addition to CO₂, hydrogen (H₂) is needed. Most commonly, the supply chains employ hydrogen production via electrolysis. Commonly, the synthesis processes allowing the synthesis of numerous products (“X”) using (renewable) electricity such as those offered by INERATEC, are called “power-to-X” (PtX).

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1. About this study

This report discusses potential environmental implications of power-to-X technology. The results presented are based on scientific literature on PtX processes. PtX processes use a carbon source (usually CO₂), hydrogen (usually produced via electrolysis) and convert these to numerous products. Electrolysis requires high amounts of electricity. Given the vast number of potential means of providing CO₂ and hydrogen, as well as possibilities to provide electricity, **Planet A decided to build its assessment upon available scientific studies**. Due to the complexity of potential supply chains and markets (different CO₂ sources, means of electricity generation, produced products addressed markets, etc.), this approach provides the most comprehensive view on the subject matter possible.

It is also important to emphasize that INERATEC provides technologies that are part of a complex supply chain ranging from raw material supply (CO₂, hydrogen), electricity generation, product distribution to use and end of life. These supply chains are embedded in a complex socio-technical system that relies on political frameworks, infrastructure developments, consumer demands etc. **The assessment does not focus on that part of the overall supply chain that is being covered by INERATEC (that is, reactor technology), but includes elements outside the range of INERATEC's influence** such as electricity generation and CO₂ supply (including infrastructure) and discusses a selection of environmental impacts of the overall supply chain. As a consequence, a share of the overall potential environmental impact is not being allocated to INERATEC. The reason behind this approach is that INERATEC provides key technologies that are likely to present an integral part of future PtX supply chains. As Planet A, we are interested in the overall potential environmental impact such supply chains could evoke.

Please note: The presented results are based on a study published by the German Environment Agency (Umweltbundesamt) and ifeu (Liebich et al. 2020). Therefore, processes might not be fully identical to processes employed by INERATEC. For instance, different catalysts might be used, processes and overall efficiencies might slightly differ. Regardless of these differences, it is considered that the reported environmental impacts provide a good indication of the potential implications of PtX technologies, such as those provided by INERATEC.

It is not possible to investigate or include all possible combinations of raw material and electricity supply in this study. The discussed supply chains and modalities included, however, reflect the most important and likely supply chains of PtX processes that could be realized using INERATEC's technology.

On the terminology "PtX": In this study, the terminology PtX is solely used for processes yielding certain hydrocarbons, i.e. liquid or gaseous fuels, waxes and methanol. Other technologies that use electricity to produce other products than hydrocarbons, such as hydrogen, hydrogen peroxide, ammonia or proteins (Daiyan et al. 2020; Molitor et al. 2019) are not included in the scope of the assessment.

2. System description

INERATEC's technologies comprise a variety of synthesis processes, including synthesis gas production via steam-assisted catalytic partial oxidation (CPOX) or reverse water gas shift (RWGS), Fischer-Tropsch (FT) synthesis, methanol synthesis and direct methanation of CO₂. These synthesis processes convert CO₂ or CO and hydrogen to hydrocarbon fuels and chemicals. Hydrogen is usually obtained via electrolysis. Several potential electrolysis technologies are currently available on the market and/or being developed (Subramani et al. 2015; Schmidt et al. 2017).

Electrolysis technologies:

- **Proton exchange membrane (PEM):** A PEM electrolyzer comprises an electrolyte that conducts protons. At the anode, water is converted to a proton (H^+), molecular oxygen (O_2) and electrons. The proton passes through the membrane to the cathode, where it is converted to hydrogen. PEM electrolyzers usually operate at low temperatures (between 50 and 80°C) and at pressures below 200 bar. They are able to run at flexible capacities and exhibit a cold start of less than 20 minutes. The advantages of PEM electrolyzers are the highly compressed pure hydrogen product and the flexible operation at different loads. The disadvantages of PEM are (at the present state of development): catalyst (e.g. platinum) and membrane material costs, water purity requirements and the complexity (compared to the other types).
- **Alkaline water (AEL) electrolyzers:** In the AEL process, water is converted into hydrogen and hydroxide (HO^-) at the cathode. The hydroxide ions travel through the electrolyte (an aqueous solution containing an alkali, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH)) to the anode, where oxygen and water are produced. Another well-established concept is the chlor-alkali electrolysis. In this process, the cathode reaction is the same. At the anode side of the electrolyzer, chloride ions (Cl^-) from a sodium chloride solution are oxidized to chlorine. Na^+ passes through a selective membrane to the cathode, where sodium hydroxide is formed. The process yields hydrogen, chlorine gas and sodium hydroxide. The chlor-alkali electrolysis is widely used to produce chlorine and sodium hydroxide. Alkaline electrolyzers usually operate at low temperatures (below 100°C) and low pressures (below 30 bar). AEL systems are less load flexible than PEM. The advantages of these systems are the relatively low capital costs and mature technology.
- **Solid oxide electrolyzer cells (SOEC):** In an SOEC, water is converted to hydrogen and oxygen ions (O^{2-}) at the cathode. A ceramic material serves as an electrolyte that transfers oxygen ions to the anode, where it is converted to molecular oxygen. SOEC operate at high temperatures (~500 to 950°C). SOEC have a high electrical efficiency and a low load flexibility.

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

- **Direct air capture:** currently, DAC is the most discussed option to directly obtain CO_2 from the atmosphere. The technologies usually use an absorbent (e.g. amine-based or caustic sorbent) or adsorbent to absorb/adsorb CO_2 . In a subsequent step, CO_2 is desorbed and compressed.
- **Industrial point-sources:** Certain industrial processes produce large amounts of CO_2 due to the combustion of (fossil) fuels or as a result of other chemical reactions. The main source of anthropogenic CO_2 is fuel combustion (e.g. power plants, refineries, kilns etc.). In addition, other processes emit process-based CO_2 . For example, clinker production emits large amounts of CO_2 in the process of calcination (converting calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and CO_2). Aside from these fossil CO_2 sources biogenic carbon sources are available to obtain CO_2 . Photosynthesis converts atmospheric CO_2 to organic matter. The carbon stored in biomass can be converted to synthesis gas (an intermediate product in most PtL processes), e.g. via gasification. Alternatively, CO_2 can be obtained via anaerobic digestion (biogas production) or combustion processes (combustion of biogas, liquid biofuels or direct combustion of biomass). There are numerous technologies to obtain CO_2 from any point source mentioned, such as absorption by chemical solvents, adsorption by solid sorbents (e.g. zeolites), membrane

separation, pressure/vacuum swing adsorption. Alternatively, the combustion process itself can be modified by using pure oxygen as the oxidizer in the combustion process (as opposed to air, containing nitrogen and trace gases). This can be achieved by oxy-fuel combustion or chemical looping combustion. These processes deliver a pure stream of CO₂ and water (vapour). Additionally, chemical looping reforming can be used to obtain synthesis gas.

Synthesis Units: INERATEC offers several modular synthesis units that comprise several conversion and processing steps.

- **Power-to-Liquid (PtL) synthesis unit:** The PtL unit comprises a RWGS reactor, a synthesis reactor (FT synthesis or methanol synthesis) and downstream processing. The RWGS reactor converts CO₂ and hydrogen to synthesis gas. Subsequently, either a FT reactor is installed producing liquid fuels (gasoline, diesel & kerosene) as well as synthetic waxes. Alternatively, a methanol synthesis unit can be installed. A downstream processing unit can be utilized to separate and upgrade the different products.
- **Power-to-Gas (PtG) synthesis unit:** The PtG system comprises a methanation reactor. The methanation reactor allows the direct conversion of CO₂ and CO to synthetic natural gas (SNG).
- **Gas-to-Liquid (GtL) synthesis unit:** In a first step, a steam-assisted CPOX reactor produces synthesis gas from methane. CPOX is a partial oxidation process that uses catalysts to maximize the exothermic reaction. The catalyst enhances product selectivity and allows the reduction of the process temperature compared to conventional partial oxidation (Ma et al. 2019). In addition, the process allows a more modular construction and lower capital costs. Synthesis gas can be further processed to liquid products by those modules used in the PtL synthesis unit.

These reactor units can be scaled in a modular way allowing a high load flexibility.

2.1. Functional unit, system boundaries and assessed indicators

INERATEC's technologies allow for the production of liquid and gaseous fuels (e.g. gasoline, kerosene, diesel, SNG), waxes and methanol. Several functional units are chosen to account for the various products:

- 1 MJ of products of Fischer-Tropsch synthesis (gasoline, diesel, kerosene and waxes): no differentiation is made between the products because the product slate can be influenced by the operator's needs or market demands. An average FT fuel product of 1 MJ is chosen as the functional unit of synthesis units employing FT synthesis.
- 1 MJ of SNG
- 1 MJ of methanol

The scope of the assessment is the production, supply and use of these PtX products. The supply of PtX products is assumed to replace conventional (fossil) fuels, energy carriers and chemicals. All elements considered are depicted in Figure 1. This study discusses the **indicators climate change** (IPCC 2013 Intergovernmental Panel on Climate Change (IPCC) 2014) and several indicators describing resource demand, i.e. **cumulative energy demand (CED), land demand, water demand, total resource.**

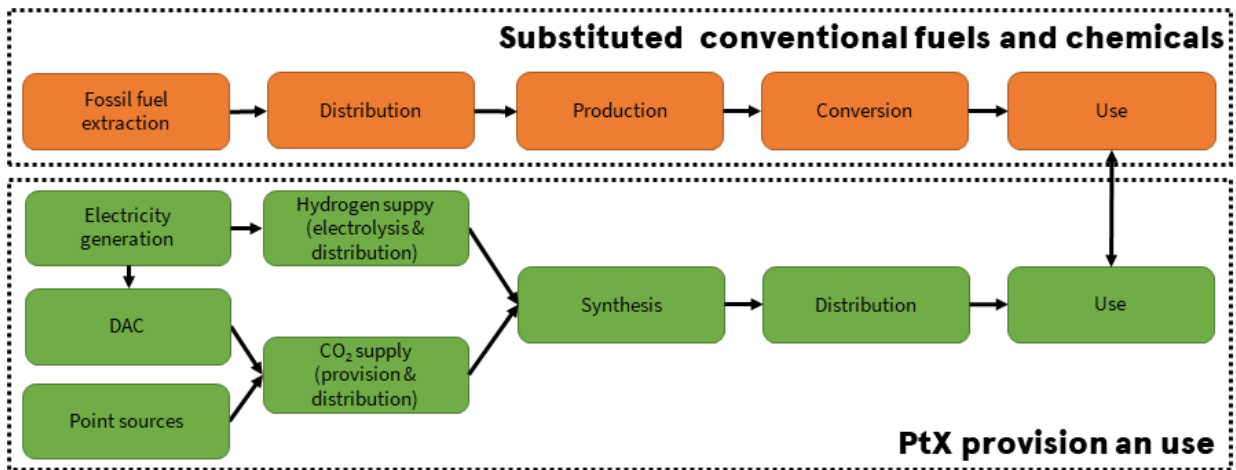


Figure 1 Depiction of system boundaries. Green processes will begin/increase operation if PtX technology enters the market; orange processes will cease to operate or reduce their production. Background processes, e.g. raw material supply, energy supply, infrastructure, waste treatment, etc. are not depicted.

2.2. PtX supply chains considered

Several combinations of the following elements of a PtX supply chain shall be considered here:

- **Hydrogen production via electrolysis:** The evaluated supply chains either use AEL, PEM electrolyzers or SOEC.
- **CO₂ supply:** The assessment contains CO₂ capturing from the atmosphere (DAC) and several industrial sources supplying fossil or biogenic CO₂ (biogas, cement factory, lignite power plant, MSW incineration plant).
- **Electricity supply:** Electricity is either supplied by wind turbines (onshore or offshore), solar power (solar PV or concentrated solar power (CSP)), geothermal power plants or the national German electricity mix.

The following synthesis units from Lieblich et al. (2020) are being considered in this study:

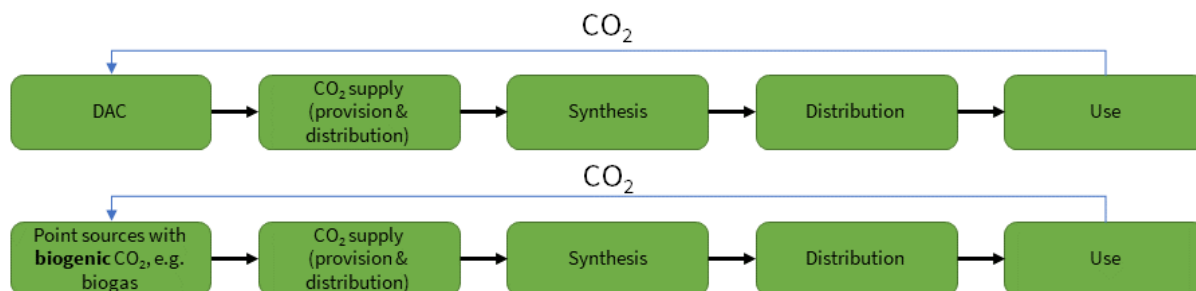
- **FT synthesis:** The FT synthesis consists of a RWGS unit, a FT synthesis unit as well as a hydrocracker and a product separation unit (rectification column). The FT synthesis uses a Co-based catalyst. The heat is used to produce steam. The steam is used in the RWGS reaction. A hydrocracker increases the production yield of short-chained hydrocarbons from the wax fraction. The overall process converts 98% of carbon dioxide to hydrocarbon products. The overall efficiency of the process is 75%. The FT synthesis yields naphtha, diesel, kerosene and waxes. The latter can be converted to liquid hydrocarbons by a hydrocracker.
- **Methanol:** Similar to the FT synthesis, synthesis gas is produced in a RWGS reactor. In a subsequent step, CO₂ is removed from the syngas stream. Afterwards, methanol is synthesized using a catalyst. In the final step, methanol is separated.
- **SNG synthesis:** SNG is directly produced catalytically using CO₂ and hydrogen. After the SNG synthesis, the gas is dried and compressed.

A complete list of all supply chains can be found in Tables A.1 to A.3. There might be slight differences in overall efficiencies of synthesis processes as Liebig et al. (2020) assessed large-scale PtX production

whereas INERATEC builds smaller, modular synthesis units. These might differ slightly in efficiencies and in the material requirements for synthesis unit construction.

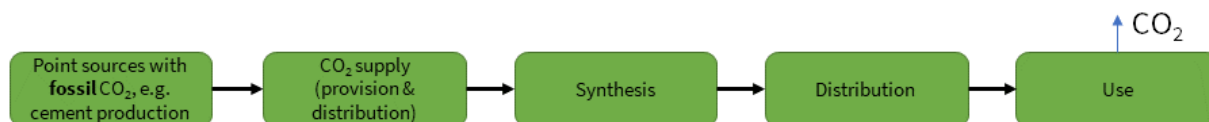
2.3. Accounting of GHG emissions from PtX product use

The assessed PtX supply chains use CO₂ from different sources. If **atmospheric CO₂** is used, CO₂ can either be directly or indirectly captured from the atmosphere using DAC or photosynthesis, respectively. In both cases, the amount of CO₂ captured approximately equals the amount of CO₂ that is emitted to the atmosphere when the PtX products are used.



If **biogenic carbon** sources are used, temporal aspects might be relevant: if wood is used, it will take several years until the same quantity of CO₂ is stored in wood again. This might result in a burden shifting to future years. In this study, biogas is used as a source of CO₂. Usually, biogas is produced from annual crops and residues of these. Therefore, CO₂ is stored in biomass again in a very short period of time.

CO₂ of fossil origin can also be used to synthesize PtX products, for example, CO₂ captured in flue gas from fossil fuel powered power plants or captured from cement factories. In contrast to the previously discussed scenarios there is no closed loop in such cases:



The question arising from these examples is how CO₂ emissions from fuel use should be attributed. This depends on the perspective:

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

For certification purposes or emission trading, it might be required to allocate emissions to specific elements in the supply chain. Using the above examples, it is of considerable interest, who is responsible for CO₂ emissions from PtX use: is the cement factory responsible for these CO₂ emissions or is it the user of PtX fuels (or any other party that is responsible for producing, selling, distributing or using the fuel)? In order to avoid loopholes in GHG emission accounting, one party within the supply chain must be held accountable for these emissions. If such an allocation is required, there would not be any emissions from PtX product use to be allocated in case of the first two examples because there is a closed (accounting) loop. Using this approach, emissions of other processes that are not part of the overall supply chain do not matter.

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

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

In the first two examples, there is a closed loop and no net emissions (from product use) occur if PtX production begins wide-scale operation. At the same time fossil CO₂ might still be in other processes, such as existing cement factories. In these cases, existing point sources emitting fossil CO₂ remain unaffected by the PtX supply chain. Hence, there are no net changes in CO₂ emissions in the overall system (PtX supply chain and other existing point sources emitting fossil CO₂). In the last example, fossil CO₂ is still emitted. Instead of a direct emission at the point source a cascade use of CO₂ is facilitated: the recycled CO₂ is emitted when PtX is used (e.g. combusted). Caveat: This assumption is valid as long as there is no wide-scale use of carbon capture and storage (CCS) technologies. If CCS became a standard in the industries, PtX would lead to the avoidance of the long-term storage of CO₂.

In all these examples, a ramp up PtX production does not affect CO₂ emissions emitted by existing emitters in the existing system.

Which approach is chosen in this report and why?

The purpose of this report is to evaluate potential changes in GHG emissions (and other indicators) as a consequence of the start of wide-scale PtX supply and use. These changes comprise all emissions emitted within the supply chain and changes in emissions occurring in other sectors of the economy. Hence, the report considers the displacement of (fossil) counterparts. The previous examples show that CO₂ emissions from other point sources are likely to remain unaffected. There is thus no differentiation made between these cases.

It is strongly emphasized that this approach does not serve certification or accounting. In such cases, fossil CO₂ emitted must be allocated to processes within the supply chain (either to the point source or to the sector in which the product is used, e.g. the transportation sector). It is also important to note that the (political) decision to promote certain supply chains might entail long-term consequences for the ambitions to reach net zero GHG emissions at a certain point in time globally. To achieve this, all sectors must decrease GHG emissions. Promoting the cascade use of CO₂ from point sources that emit fossil CO₂ might prolong the existence of these point sources. Hence, from a holistic perspective, promoting CO₂ use from fossil point sources should only be considered in those cases where emission reductions are not possible and where no alternative to these processes exists (e.g. calcination in cement production).

2.4. Life cycle inventory

The following section provides a brief summary of the most important parameters and inventory data. For a detailed description of the full inventory the reader is referred to the (Liebich et al. 2020) and additional data supplied¹.

¹ Additional information and data can be accessed on <https://www.umweltbundesamt.de/publikationen/system-comparison-of-storable-energy-carriers-from> (last accessed Aug 17 2021).

2.4.1. Key technical parameters of renewable energy generation

One key element of the PtL supply chain is electricity supply. Table 1 lists the technical parameters of renewable energy provision. The LCI used in (Liebich et al. 2020) stems from the ecoinvent database (Wernet et al. 2016). The energy potential of renewable energy sources was determined by the REMix energy model (Stetter 2014). This comprises i.a. wind speeds, solar radiation, electricity grid infrastructure, land-use etc. Table 2 shows the full load hours of different electricity production from renewable sources at different locations.

Table 1 Technical parameters of renewable energy supply (Liebich et al. 2020). If more than one value is stated, each value stands for the corresponding parameter today, in 2030 and 2050 (today/2030/2050). Abb.: CSP - concentrated solar power, Geoth. - geothermal, OF - open field, offs. - offshore, ons. - onshore, PT - parabolic trough, PV - photovoltaics, ROR - run-of-the-river, ST - solar tower, Temp. - temperature.

	Unit	PT CSP	ST CSP	PT CSP	ST CSP	Geoth.	PV RT	PV OF	RORHyd	WindOn	WindOff
Capacity	MW _{out}	100	100	100	100	303	5	5	10	2.9/3.8/6	4.15/8.5/15
Turbine eff.	%	37/40.2/43.4	42.1/42.9/44.5	37/40.2/43.4	37/40.2/43.4	17	18	16	95		
Thermal eff.	%					51					
Name plate capacity (brutto)	%	28	23	28	28						
Annual net eff.	%	17.2/18.1/19.3	12.2/13.3/15.9	17.2/18.1/19.3	17.2/18.1/19.3						
Minimum load	%	20	20	20	20						
Availability factor	[-]	96/97/98	96/97/98	96/97/98	96/97/98		1.0	1.0		980	94.1
Low. Temp. bound.	°C	293	293	293	293						
Up Temp. bound.	°C	393/485/600	565/580/650	393/485/600	393/485/600						
Lifespan	a	25	25	25	25	30	20/25/30	20/25/30	40	20/25/25	20/25/25
Degradation	%/a	0.50	0.50	0.50	0.50		0.40	0.40	0.10		
Pressure	bar	103	150	103	103						
Well depth	m					2220					
Thermal capacity	MW					133					
Hub height	m									100/115/140	90/112.5/165
Rotor diameter	m									101/124/168	120/172/235
Space	m ²	986,000	940,000	1,530,000	1,448,000						
Solar multiple		2.0	2.0	3.0	3.0						

Table 2 Full load hours of renewable electricity production (Liebich et al. 2020). Abbr.: CSP - concentrated solar power, PV - photovoltaics, SM - solar multiple.

Location	PV	CSP (without storage)	CSP SM 3	Wind onshore	Wind offshore
Morocco	1729	2063	6189	2946	3928
Saudi Arabia	1777	2179	6537	1870	1963
Germany	958	0	0	2963	4234

2.4.2. Key technical parameters of hydrogen production

The study comprises electrolysis using AEL, PEM and SOEC. SOEC entered the market only recently. At the time of the assessment only small-scale SOEC were only available. The key technical parameters of electrolyzers are listed in Table 3.

Table 3 Technical parameters of electrolyzers (Liebich et al. 2020). If more than one value is provided each value stands for the corresponding parameter today, in 2030 and 2050 (today/2030/2050). Abb.: AEL - alkaline electrolysis, LHV - lower heating value, Max. - maximum, Min. - minimum, PEM - proton exchange membrane, SOEC - solid oxide electrolyzer cell.

	Unit	AEL	PEM	SOEC
Stack efficiency	% (LHV)	71/73/80	71/75/85	>100% ²
System efficiency	%	67/69/72	67/71/80	n/a
Temperature	°C	80/85/95	85/100/100	700 - 1000
Max. pressure	bar	30/60/60	80/90/90	1
Current density	A/cm ²	0.4/0.6/0.8	2/2.5/3.5	0.4 - 2
Min. partial load	%	40/30/20	10/5/5	n/a
Stack capacity	m ³ /h	450/1250/1750	250/500/500	5.7
Total operation time	10 ³ h	75/90/90	50/80/80	10/70/90
System lifespan	a	30	30	30

² A part of the energy input is derived from waste heat from other industrial processes. Therefore, the ratio between the LHV of produced hydrogen and electricity input exceeds 100%. For further details, see Liebich et al. 2020.

2.4.3. Key technical parameters of the CO₂ capturing

There are different options available to provide concentrated CO₂ to the synthesis units. Table 4 lists the key technical parameters of technologies included in the assessment.

Table 4 Technical parameters of CO₂ sources (Liebich et al. 2020). If more than one value is provided each value stands for the corresponding parameter today, in 2030 and 2050 (today/2030/2050). Abb.: DAC - direct air capture, Ind. - industrial, PSA - pressure swing adsorption, PWS - pressurized water scrubbing

	Unit	PSA & PWS	Amine washing	Ind. CO ₂ (amine)	Ind. CO ₂ (selexol)	DAC
Operating hours	h/a	8400	8400	8410		
Biogas upgrading capacity	Nm ³ /h	1400	1400			
	t/a/module					49
CO ₂ volume flow	t/a					
Biogas from agricultural products and residues		10,478/10,478/9,838	10,478/10,47/9,838			
Biogas from organic waste		9,314/9,314/7,917	9,314/9,314/7,917			
CO ₂ content	%	93	99	98	98	
Pressure	bar			2	18 2 0.3	01.01
Electricity demand	kJ/kg CO ₂			40	1100	2520/1850/1440
Heat demand	MJ			3.8		7.92/6.57/5.76
Temp. level (lower boundary)	°C					80
Temp. level (upper boundary)	°C					120
Degradation (per cycle)	%					0.02
Lifespan	a					20

2.4.4. Key technical parameters of the synthesis units

The key technical characteristics of synthesis units is listed in Table 5.

Table 5 LCI of the synthesis units (Liebich et al. 2020). Abbr.: DAC - direct air capture, LHV - lower heating value, MeOH - Methanol, PtG - Power-to-gas, PtL - Power-to-liquid,, SNG - synthetic natural gas. The complete LCI is listed in Table A.4 in the Annex.

Capacity	MW _{out}	FT-PtL (all)	PtG (SNG)	MeOH (Rectisol)	MeOH (DAC)
		90.00	6.00	90.00	90.00
Full load hours	h/a	7,884	8,000	7,884	7,884
Hours in operation	h/a	7,884	8,000	7,884	7,884
Efficiency (LHV)	%	75	78	84	84
Efficiency (energetic)	%	75	83	86	86
Partial load flexibility			70		
Lifespan	a	25	25	25	25
Carbon efficiency	%	98		88	88
Pressure	bar	25.00	8.00	50.00	50.00

2.4.5. Other LCI aspects

The previous sections explained the key technical parameters of PtX production. Other key assumptions and modelling choices are (Liebich et al. 2020):

- Two general operating modes were evaluated in the study impacting the overall design of the supply chain: a) an operating mode that maximizes the full load hours of the synthesis unit and b) full load hours of the renewable electricity source. In the former case, hydrogen and CO₂ storages are needed. In the latter case, synthesis units are only operated when renewable electricity is available (Table 2).
- The study assumes that the overall economy is on a trajectory towards less GHG emissions according to political targets. This implies that the production of raw materials, such as steel, aluminum, plastics, cement etc. will entail lower GHG emissions in 2030 and 2050 than today.
- Transportation of fuels was modelled using the TREMOD 5.7 model. For details, please refer to (Allekotte et al. 2020).
- High voltage direct current electricity transmission was modelled with losses of 4.5%, 2.6% and 3.6% per 1000 km in case of overhead power lines, submarine power cables and underground cables, respectively.
- All supply chains operating in the MENA region (Middle East and North Africa) additionally comprise a membrane-based desalination of seawater.
- 40-45% of biogas produced in Germany is being considered as a potential source for concentrated CO₂. Biogas is produced using agricultural residues or energy crops, e.g. corn.

Corresponding data and further explanations can be found at the [website](#) of the German Environment Ministry.

3. Environmental impact of PtX supply and use

The following sections discuss GHG emissions (section 3.1) and resource demand of PtX production and use.

3.1. GHG emissions

Almost all PtX supply chains result in a net decrease in GHG emissions if fossil counterparts are displaced (Table 6, Figure 2). The average net reduction in GHG emissions in 2030 is -57 g CO₂-eq per MJ PtL fuel (gasoline, diesel and kerosene), -66 g CO₂-eq. for methanol and -40 g CO₂-eq. for synthetic natural gas. In all synthesis pathways electricity production plays the most important role in terms of GHG emissions, except for the synthesis pathway using oxy-fuel. **In 2030, almost all scenarios result in a net decrease in GHG emissions.** Only in those scenarios in which grid electricity is used in 2030 (still comprising a certain share of non-renewable electricity), no net decrease in GHG emissions is achieved. Synthesis pathways using biogas result in the lowest GHG emissions. This finding is even further enhanced if CO₂ from fossil sources is allocated to the use of PtX products (see below).

The results also show that the availability of renewable energy plays an important role: PtX production in locations with high annual full load hours result in much lower GHG emissions than those at locations with only a lower amount of full load hours. For instance, PtX production using offshore wind power in Germany or solar power in the MENA region exhibit significantly lower emissions than the use of solar PV in Germany. The comparison of the two operating modes (maximizing full load hours of the synthesis unit or operation of the synthesis only unit when renewable electricity is available) shows that the former

operating mode results in lower GHG emissions. On average (among all synthesis pathways), an operation that maximizes the full load hours of the synthesis unit results in 17% less GHG emissions. Such an operation mode increases the need for renewable electricity. It also increases the product quantity produced (and hence the displacement of fossil fuels).

The technical specification of INERATEC's modular synthesis units might differ from the large-scale facilities modelled by Liebig et al. (2020). However, the results show that the synthesis units only have a minor influence on overall results. Due to the high importance of electricity production, minor differences between the modelling data and real-world data of renewable electricity production will result in much higher deviations of modelling results from real-world emissions and impacts.

Table 6 GHG emissions of PtX provision. Upper part: only PtX supply chain. Lower part: Net change in GHG emissions if fossil counterparts are displaced. All values in g CO₂-eq. per MJ.

	PtL			MeOH			PtG			
	2015	2030	2050	2015	2030	2050	2015	2030	2050	
Only PtX	Average	57.32	33.45	18.93	64.38	28.59	21.74	43.52	22.99	11.12
	Median	25.65	21.53	13.13	35.63	20.06	17.37	21.43	14.98	10.73
	Minimum	14.69	12.91	8.29	17.90	9.90	8.66	6.87	6.59	4.42
	Maximum	374.35	132.85	85.02	346.43	124.38	124.37	301.97	106.34	32.27
	5% Percentile	15.48	13.14	8.51	18.48	9.98	8.80	7.11	6.68	4.50
	95% Percentile	374.35	132.84	84.44	346.42	105.94	77.90	301.97	106.34	25.19
	PtL			MeOH			PtG			
	2015	2030	2050	2015	2030	2050	2015	2030	2050	
Delta	Average	-32.68	-56.55	-71.07	-30.62	-66.41	-73.26	-19.48	-40.01	-51.88
	Median	-64.35	-68.47	-76.87	-59.37	-74.94	-77.63	-41.57	-48.02	-52.27
	Minimum	-75.31	-77.09	-81.71	-77.10	-85.10	-86.34	-56.13	-56.41	-58.58
	Maximum	284.35	42.85	-4.98	251.43	29.38	29.37	238.97	43.34	-30.73
	5% Percentile	-74.52	-76.86	-81.49	-76.52	-85.02	-86.20	-55.89	-56.32	-58.50
	95% Percentile	284.35	42.84	-5.56	251.42	10.94	-17.10	238.97	43.34	-37.81

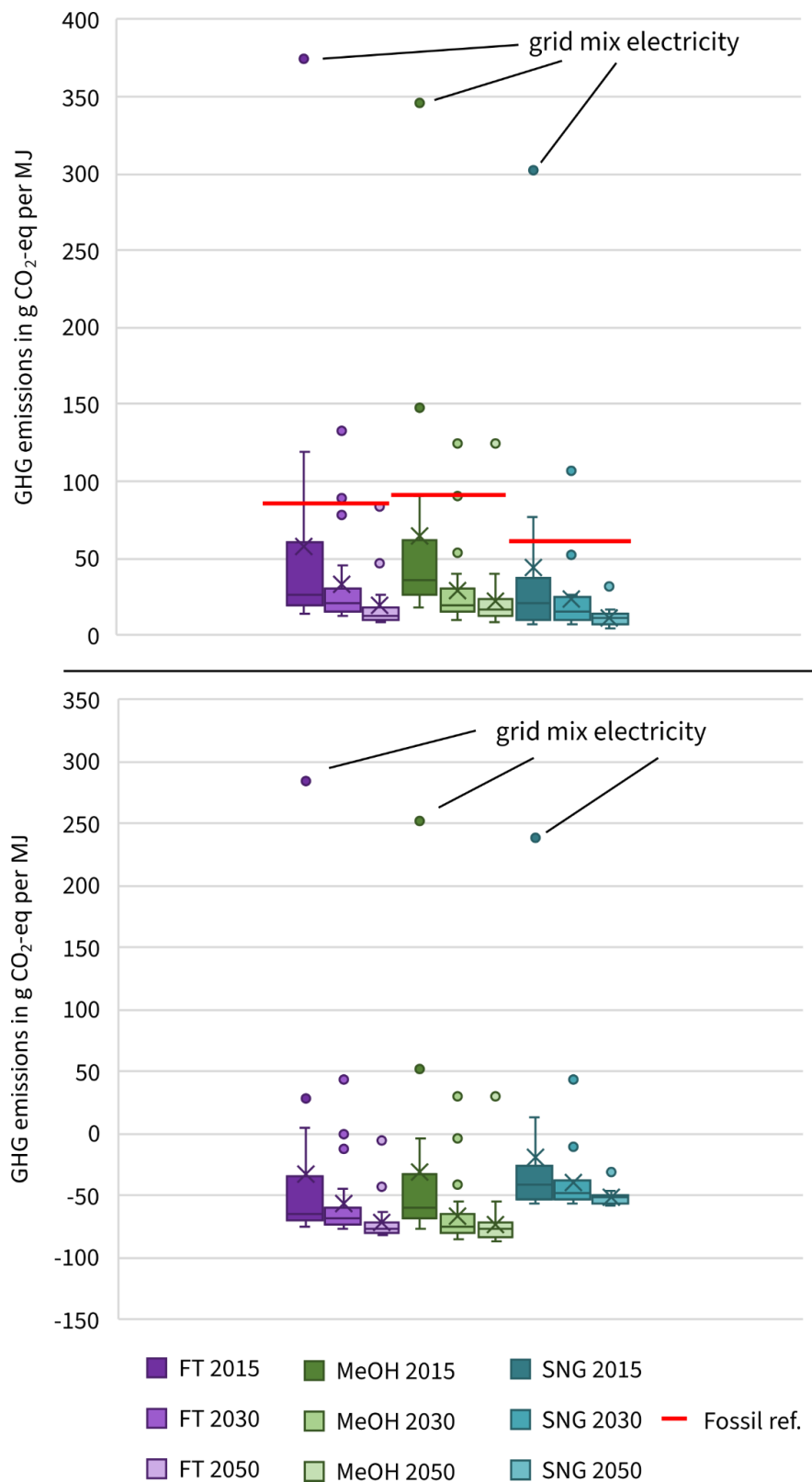


Figure 2 Top: net change in GHG emissions due to the production and use of PtX products substituting fossil reference products (data obtained from Liebich et al. 2020). PtL comprises liquid fuels commonly used in the transportation sector (gasoline, diesel and kerosene). Bottom: GHG emissions of PtX production and its fossil counterparts (Fossil. ref.). Please note: CO₂ emitted by the use of these products is not included in the graph. Please see text for further information on the attribution of CO₂ emissions of PtX product use. Abbr.: FT - Fischer-Tropsch (gasoline, diesel & kerosene), GHG - greenhouse gas, MeOH - methanol, SNG - synthetic natural gas.

3.2. Resources

The resource demand of PtX synthesis pathways is substantially higher than the comparable resource demand of fossil counterparts (Table 7). For all indicators, electricity supply is the largest contributor to indicator scores. It should be noted that the study conducted by Liebich et al. (2020) does not report on various fossil energy demand separately, which would better capture the use of fossil (finite) resources. Furthermore, it should be noted that all indicators presented here are mid-point indicators, e.g. summarizing land demand without categorizing land. The impact of land and water demand strongly depends on local conditions: where land is used, what type of land is used and where water is extracted and used. The impacts of using land on the environment and society might differ substantially depending on what type of land is used (e.g. desert land for solar PV vs. wind power in populated areas). Due to their high energy density, liquid PtX products can be produced in regions, with low overall impact or land-use competition (e.g. arid areas in the MENA region or in Patagonia). As this study presents only a generalized overview of potential environmental implications of PtX production, more localized analysis of specific PtX projects could give a better indication of the localized impacts of land and water demand. These results indicate that there might be an increase in land demand and future PtX projects should be located in areas where they cause the lowest potential impact.

Table 7 Resource demand of PtX production. Results obtained from (Liebich et al. 2020). Abbr.: CED - cumulative energy demand, CRD - cumulative resource demand, FT - Fischer-Tropsch, Max - maximum, MeOH - Methanol, Min - minimum, perc. - percentile, ref. - reference, SNG - synthetic natural gas.

PtX	Indicator	Unit	Average	Mean	Min	Max	5% perc.	95% perc.	Fossil ref.	% of fossil ref.
FT	CED	MJ/MJ	2.59	2.34	02.08	5.94	02.08	02.08	1.20	216%
	CRD	kg/MJ	0.07	0.07	0.02	0.20	0.02	0.02	0.03	257%
	Land	m ² *a/MJ	6.18 10 ⁻³	2.15 10 ⁻³	4.92 10 ⁻⁴	2.59 10 ⁻²	4.94 10 ⁻⁴	4.94 10 ⁻⁴	9.40 10 ⁻⁵	6.577%
	Water	L/MJ	0.46	0.32	0.14	2.65	0.14	0.14	0.07	689%
MeOH	CED	MJ/MJ	2.64	2.37	02.02	5.84	02.03	02.03	1.60	165%
	CRD	g/MJ	0.08	0.07	0.02	0.25	0.03	0.03	0.04	202%
	Land	m ² *a/MJ	7.66 10 ⁻³	3.43 10 ⁻³	3.57 10 ⁻⁴	2.97 10 ⁻²	4.38 10 ⁻⁴	4.38 10 ⁻⁴	1.90 10 ⁻⁴	4.034%
	Water	L/MJ	0.90	0.32	0.04	5.58	0.07	0.07	0.05	1.882%
SNG	CED	MJ/MJ	1.85	1.80	1.49	2.50	1.49	1.49	01.01	184%
	CRD	g/MJ	0.05	0.04	0.03	0.13	0.03	0.03	0.03	203%
	Land	m ² *a/MJ	5.49 10 ⁻³	7.13 10 ⁻³	2.69 10 ⁻⁴	1.80 10 ⁻²	2.70 10 ⁻⁴	2.70 10 ⁻⁴	5.40 10 ⁻⁸	10,160,967%
	Water	L/MJ	0.19	0.15	0.11	0.45	0.11	0.11	0.00	175.055%

3.3. Comparison with other studies

There are a few studies that evaluate the environmental implications of PtX fuels or products:

- A study accompanying the [Kopernikus P2X](#) project evaluates several PtX supply chains (Ausfelder and Dura 2019). The study reports similar findings as presented in this report. For instance, PtX products result in lower GHG emissions than their fossil counterparts only if electricity from renewable sources with low GHG emissions is used. Furthermore, PtL fuels only result in lower GHG emissions than fossil fuels if CO₂ emissions from fuel combustion are not assigned to the fuel use in case CO₂ used for the synthesis is obtained from point sources emitting fossil CO₂³. The study reports higher resource demands (land, water, energy) than the fossil counterparts which is also in line with the results presented in this study. The increase in resource demand in comparison with fossil fuels results from the additional capacity of renewable energy provision (e.g. wind turbines and solar PV panels).
- Hannula and Reiner (2019) report that PtL fuels using electricity from renewable sources emits between 5% and 16% of GHG emissions from fossil fuels (Hannula and Reiner 2019). Similar to the results shown in this study using grid electricity results in substantially higher GHG emissions.
- Schmidt et al. (2018) compare several alternatives to conventional aviation fuels. As concluded in this study and the previously mentioned studies, PtL results in significantly lower GHG emissions than conventional aviation fuel (Schmidt et al. 2018).

The literature review reveals that PtX fuels are performing much better than fossil counterparts in terms of GHG emissions. However, they perform worse with regards to resource consumption.

3.4. Brief discussion of other alternatives to fossil fuels

There are numerous alternatives to fossil fuels in the transportation sector. The following section presents a brief discussion on the suitability of these alternatives.

1. Potentials

Certain transportation modalities rely on fuels with high energy density. In the aviation and shipping industries for example there are only few alternatives in sight that could make liquid fuels obsolete within the timeframe needed to combat climate change in an effective and timely manner:

- **Biofuels:** A widely discussed alternative to fossil kerosene and fossil bunker oil is biofuels. There are numerous pathways to obtain fuels from all types of biomass, e.g. lignocellulose, sugars, fats and starch (Neuling and Kaltschmitt 2018). Biofuels made from crops that are dedicatedly grown for biofuel production require vast land areas and water resources (Buchspies and Kaltschmitt 2018). If land-use change (direct (dLUC) and indirect (iLUC)) are considered, GHG emissions could exceed the GHG intensity of fossil. Biofuels are mostly cultivated on fertile land that could either be used for the production of food, feed and fiber or as a natural habitat. Scientific literature reports a range of 30 to 120 EJ of bioenergy potential globally (Roth et al. 2018). This would be sufficient to provide a considerable amount of biokerosene (the pre-pandemic kerosene demand

³ Please see section 2.3 for further details on the assignment of CO₂ emissions of fuel combustion. Furthermore, Ausfelder and Dura (2019) provide a detailed discussion on how CO₂ used as feedstock can be considered. The authors provide an extensive discussion on how to consider different origins of CO₂ (e.g. industrial point sources emitting fossil CO₂, biogenic CO₂ or CO₂ obtained from DAC).

was 17 EJ per year). It should be noted that using land for cultivation of (energy) crops and especially expanding land to do so entails severe environmental and social risks, such as biodiversity loss and increase in staple food prices, cf. (Buchspies and Kaltschmitt 2018). Large-scale biofuel projects have been criticized for disrespecting land rights of local communities, too. Using biomass residues alleviates certain key pressures but a sustainable use of residues is unlikely to be able to serve the demand for kerosene.

- **Hydrogen:** Aircraft and ship manufacturers develop aircrafts propelled by hydrogen used in fuel cells or combusted in gas turbines. Compared to liquid PtX fuels, hydrogen used in fuel cells exhibits a higher overall efficiency (well-to-wing). This presents an advantage over liquid PtL fuels because less additional renewable electricity capacities are needed. Using hydrogen in a combustion engine reduces the overall efficiency drastically. A main challenge of using hydrogen is the comparably low volumetric energy density resulting in high space requirements in the aircraft. The additional space requires a re-design of aircrafts, e.g. location and dimensioning of tanks or complete redesign of fuselage and wings. Therefore, a wide-scale application of hydrogen in the aviation industry will take several years (see below).
- **Battery electric propulsion:** At the present state of battery development the energy density is by far too low to operate large-sized airplanes or container ships. Even if these aircrafts and ships were developed in the upcoming decade the replacement rates of the aviation fleet would still be too slow to combat climate change in a timely manner.
- **Other approaches discussed in the maritime sector:** The shipping industry discusses liquified natural gas (LNG), liquefied petroleum gas (LPG), methanol and wind propulsion. The first three options usually refer to less polluting fossil fuels. However, LNG and methanol could also be produced by technologies discussed in this study.

In contrast to the aviation and maritime sectors, which are hard to decarbonize, viable options exist in most road transportation sectors. Electrification using batteries or hydrogen present viable options to replace fossil fuel-driven combustion vehicles. There are numerous studies demonstrating that electric vehicles emit less GHG emissions than fossil fuel-driven vehicles if operated using electricity from renewable sources (Verma et al. 2021). A comprehensive review of LCA studies on resource consumption of battery electric vehicles (BEV) shows that most available LCA literature indicates higher resource demands of BEV in comparison to conventional vehicles (Dolganova et al. 2020). A key indicator that is often used to compare (battery) electric vehicles with vehicles using PtX fuels is efficiency.

2. Efficiency

The overall efficiency from well-to-wheel, -wake or -turbine is an important parameter to compare several potential substitutes of fossil-based transportation options. The overall efficiency of the process chain gives an indication of the additional renewable energy capacity needed to be installed to fulfill the future demand for energy. Additionally, it gives an indication of the demand for resources and expenditures to install the necessary infrastructure. Many studies highlight the overall process efficiency of electric vehicles compared to PtL fuels. Influential studies report overall process chain efficiencies of 77%, 30% and 13% in case of BEV, fuel cell vehicles (FCEV) using hydrogen and PtL fuels, respectively (Ash et al. 2020; Transport & Environment (T&E) 2020). One study puts these figures into context by analyzing areal demands for renewable energy in Europe if the additional renewable energy was supplied by offshore wind

energy. In a base case scenario (51% BEV, 27% FCEV, 22% PtL) an area 3.4 times the size of Denmark would be needed. In a high hydrogen scenario (31% BEV, 48% FCEV, 21% PtL) and a high PtL scenario (16% BEV, 14% FCEV, 79% PtL), the demand for offshore wind turbines would measure 4 and 5 times the area of Denmark, respectively. This indicates that a higher share of PtL use in the transportation sector requires significant additional renewable energy capacities. These estimations omit some key aspects: transportability of different types of energy as well as the difference in the efficiency of renewable energy generation. Figure 3 shows that the efficiency of renewable energy installations differ significantly depending on where they are installed. Producing PtL fuels in regions with high wind and solar potential significantly reduces the space (and resources) required to install the infrastructure. Due to the transportability of PtX products PtX synthesis can be conducted at locations where there is the highest potential for renewable energy. Additionally, they can be produced in regions with low population densities thereby avoiding conflicts of interest with the public or in areas with low biodiversity. In contrast, BEV charged with electricity from the grid are dependent on local (renewable) electricity generation. Consequently, the advantages of direct electrification might be far less pronounced if the production of PtL fuels from other regions is taken into account: the space requirements highlighted above are based on offshore wind power. If other renewable sources were taken into consideration the space requirements increased (in all scenarios). However, PtL could be produced elsewhere with a much higher yield resulting in a less pronounced space and material demand compared to BEV (if at all).

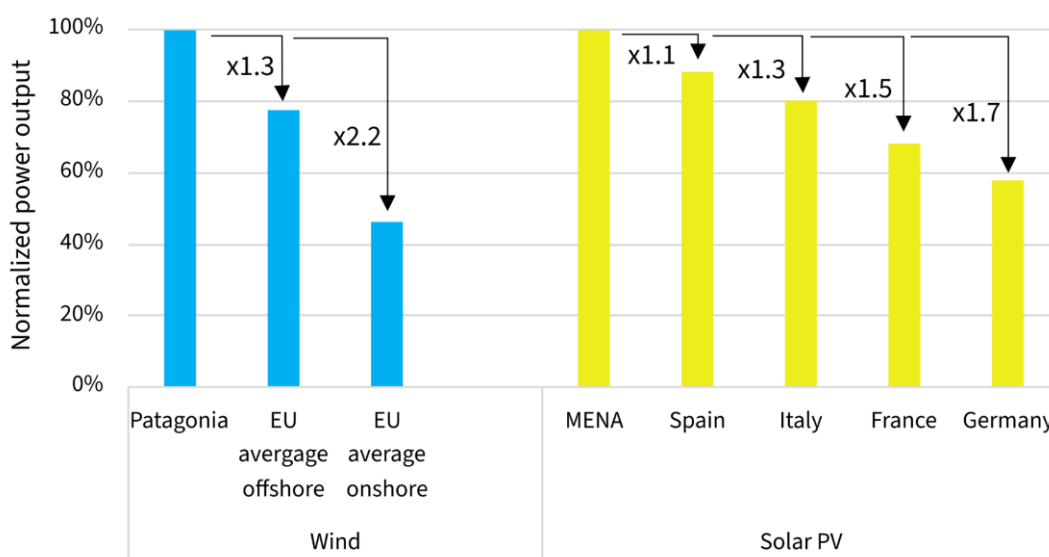


Figure 3 Normalized power output of wind and solar PV at selected locations per installed capacity. The multiplier denotes the additional capacity requirements in comparison to the chosen location with the highest energy output. Data sources: (Heuser et al. 2019; Komusanac et al. 2021; Energy Sector Management Assistance Program (ESMAP) 2020).

3. Infrastructure and temporal aspects

Reducing the risk of most adverse effects of climate change requires a timely and efficient reduction in GHG emissions. The construction of infrastructure takes time and might require substantial expanses of resources (entailing more GHG emissions). Additionally, the replacement rates of aircraft fleets and adoption speed of new technologies is slow: Oguntona (2020) shows

that replacing fuels is the most efficient and fastest way to reduce GHG emissions in the time horizon to 2050 (Oguntona 2020). Fuel replacement could achieve a net reduction in GHG emissions of nearly 60% (in this case, biofuels were assessed). In contrast, hardware-based solutions could only deliver less than 20% emission reduction in the same time frame. **Providing fuels with significantly lower GHG emissions is thus the fastest and most efficient way to reduce GHG emissions in the aviation industry.** Likewise, ships have a long life-time making fleet replacement rates very slow. Hence, optimizing existing ships and their operation, e.g. by slow steaming and better routing, as well as replacing fuels used might be the fastest way to mitigate climate change.

Temporal aspects of technology ramp-up should therefore be taken into consideration when comparing different options to reduce the dependency on fossil energy sources. The explanations above indicate that in certain sectors (e.g. motorized road vehicles), electrification might be the quickest option. This might still be accompanied by PtL fuels in order to provide the required quantities of energy to the transportation sector). Other transport modalities with much slower infrastructure replacement rates require solutions that can be used as fast as possible, e.g. so called 'drop-in' fuels, such as PtL fuels.

4. Conclusion

The substitution of fossil-based hydrocarbons in the transportation sector and the chemical industry poses a major challenge to addressing climate change. INERATEC's PtX technology provides synthesis units that allow the production of gaseous and liquid hydrocarbon fuels and chemicals that can directly replace currently used fossil fuels and chemicals. The production of these PtX products require a carbon source, such as CO₂ from industrial point sources or captured from the atmosphere and hydrogen. In future, hydrogen will likely be provided by electrolysis of water, requiring large amounts of electricity. The results presented in this study show that **PtX products outperform conventional, fossil-based fuels and chemicals by far in terms of GHG emissions, if electricity is provided from renewable sources. In all scenarios in which electricity from renewable sources is used, a substantial net reduction in GHG emissions can be expected if fossil-based hydrocarbons are displaced.** It is therefore important to ensure that PtX fuels are produced using renewable energy. **In terms of resource demand, PtX fuels perform worse than conventional fossil fuels.** This is due to the resource demand for additional infrastructure requirements, i.e. capacity of renewable electricity.

A comparison with other options shows that resource demand might be a critical issue, too (e.g. BEV). In comparison to battery electric propulsion, **PtX can easily be used in the transportation sector without any modification of existing infrastructure.** This is especially relevant in the case of the aviation and maritime sectors. Providing alternatives to fossil fuels and chemicals in a timely manner is especially important when considering the time frame remaining to evade the most severe consequence of climate change. The overall requirements for additional capacity of electricity from renewable sources is a challenge to be met in the upcoming decades. **BEV exhibit a higher well-to-wheel efficiency but relies on localized electricity supply. PtX fuels used in combustion engines have a lower overall efficiency but allow the production of fuels and chemicals in regions, where there is a much higher potential for renewable energy production.** This fact reduced the needed additional capacity in comparison to BEV. Furthermore, energy from **renewables can be provided and converted into PtX products in regions with lowest sustainability impacts**, such as biodiversity loss or land-use competition.

The future transportation sector must rely on several options to fulfill the demands for transportation and mobility services. Hydrocarbons used in the chemical industry must be provided by renewable means, too. Ultimately, all alternatives to fossil-based fuels and chemicals will require a trade-off of economic, environmental and social impacts. These trade-offs will need to be made when combating climate change in a timely manner. It is therefore important that each alternative technology is used in the most efficient and sustainable way in those sectors, where there is no better alternative. Especially in the maritime and aviation sectors, PtX fuels are the most promising solutions to combat climate change.

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Annex

A.1 Assessed supply chains

Table A1 Assessed FT supply chains. Selection of supply chains taken from (Liebich et al. 2020). Abbr.: AEL - alkaline electrolyzer; CSP - concentrated solar power; DAC - direct air capture; HDV - heavy duty vehicle; HVDC - high-voltage direct current; MSW - municipal solid waste; PEM - proton exchange membrane electrolyzer; PV - photovoltaics; SOEC - solid oxide electrolyzer.

Location of synthesis	CO ₂ source	Electricity supply	Electrolysis	Transport
Germany	Biogas power plant	Wind onshore	AEL	HDV
Germany	Cement factory	Solar PV	AEL	HDV
Germany	Cement factory	Solar PV (Saudi Arabia)	AEL	HVDC transmission + HDV
Saudi Arabia	Cement factory	Solar PV	AEL	Tank vessel + HDV
Saudi Arabia	Cement factory	CSP	AEL	Tank vessel + HDV
Germany	DAC	Solar PV	AEL	HDV
Germany	DAC	Wind offshore	AEL	HDV
Morocco	DAC	CSP	AEL	Tank vessel + HDV
Morocco	DAC	Wind onshore	AEL	Tank vessel + HDV
Morocco	DAC	Solar PV	AEL	Tank vessel + HDV
Iceland	DAC	Geothermal power plant	AEL	Tank vessel + HDV
Germany	DAC	Wind offshore	SOEC	HDV
Germany	Biogas power plant	Wind onshore	PEM	HDV
Germany	Lignite power plant	Wind onshore	AEL	HDV
Germany	Lignite power plant	Electricity mix	AEL	HDV
Germany	Oxyfuel-Lignite power plant	Wind onshore	AEL	HDV
Germany	MSW incineration	Wind onshore	AEL	HDV

Table A2 Assessed SNG supply chains. Selection of supply chains taken from (Liebich et al. 2020). Abbr.: AEL - alkaline, CSP - concentrated solar power, electrolyzer, HDV - heavy duty vehicle, HVDC - high-voltage direct current, MSW - municipal solid waste, PV - photovoltaics.

Location of synthesis	CO ₂ source	Electricity supply	Electrolysis	Transport
Germany	Biogas power plant	Wind onshore	AEL	Natural gas grid
Germany	Cement factory	Solar PV	AEL	Natural gas grid
Germany	Cement factory	Solar PV (Saudi Arabia)	AEL	HVDC transmission + HDV
Saudi Arabia	Cement factory	Solar PV	AEL	Pipeline
Saudi Arabia	Cement factory	Solar PV	AEL	Tank vessel + Natural gas grid
Germany	DAC	Solar PV	AEL	Natural gas grid
Germany	DAC	Wind offshore	AEL	Natural gas grid
Morocco	DAC	CSP (Morocco)	AEL	HVDC transmission + HDV
Morocco	DAC	CSP	AEL	Pipeline
Morocco	DAC	CSP	AEL	Tank vessel + Natural gas grid
Germany	Lignite power plant	Wind onshore	AEL	Natural gas grid
Germany	Lignite power plant	Electricity mix	AEL	Natural gas grid

Table A3 Assessed methanol supply chains. Selection of supply chains taken from (Liebich et al. 2020). Abbr.: AEL - alkaline, CSP - concentrated solar power, electrolyzer, HDV - heavy duty vehicle, HVDC - high-voltage direct current, MSW - municipal solid waste, PV - photovoltaics.

Location of synthesis	CO ₂ source	Electricity supply	Electrolysis	Transport
Germany	Biogas power plant	Wind onshore	AEL	HDV
Germany	Cement factory	Solar PV	AEL	HDV
Germany	Cement factory	Solar PV (Saudi Arabia)	AEL	HVDC transmission + HDV
Saudi Arabia	Cement factory	Solar PV	AEL	Tank vessel + HDV
Saudi Arabia	Cement factory	CSP	AEL	Tank vessel + HDV
Germany	DAC	Solar PV	AEL	HDV
Germany	DAC	Wind offshore	AEL	HDV
Morocco	DAC	CSP	AEL	Tank vessel + HDV
Morocco	DAC	Wind onshore	AEL	Tank vessel + HDV
Morocco	DAC	Solar PV	AEL	Tank vessel + HDV
Iceland	DAC	Geothermal power plant	AEL	Tank vessel + HDV
Germany	Biogas power plant	Wind onshore	PEM	HDV
Germany	Lignite power plant	Wind onshore	AEL	HDV
Germany	Lignite power plant	Electricity mix	AEL	HDV

A.2. Additional Life Cycle Inventory (LCI)

Table A4 Additional LCI of the synthesis units (Liebich et al. 2020). Abbr.: DAC - direct air capture; FT - Fischer-Tropsch, MEA - monoethanolamine, MeOH - Methanol, PtL - Power-to-liquid, LHV - lower heating value, SNG - synthetic natural gas.

Input	Unit	FT-PtL (Selexol)	FT-PtL (MEA)	FT-PtL (DAC)	PtG (SNG)	MeOH (Rectisol)	MeOH (DAC)
Hydrogen	t/a	31,200	31,200	31,200	1,080	32,000	32,000
Carbon dioxide	t/a	202,000	202,000	202,000	5,875	260,000	260,000
Selexol	t/a	2.0					
MEA	t/a		300.00	300.00			
Catalyst (Cr ₂ O ₃)	kg/a					4,037	4,037
Catalyst (Cobalt)	kg/a	1,808	1,808	1,808			
Catalyst (Nickel)	kg/a				388		
Water	t/a	240,000	240,000	240,000		240,000	240,000
Cooling water (net)	t/a	10,350,000	10,350,000	10,350,000	⁻⁴	10,350,000	10,350,000
Electricity	GJ/a			509,040	1,900		655,200
Heat	GJ/a						
Warm water	GJ/a			253,462			1,519,934
Output							
FT-Products	t/a	64,420	64,420	64,420			
SNG	t/a				2,200		
Methanol	t/a					150,000	150,000
Water ⁵	t/a				4,745		
Electricity	GJ/a	22,700	70,000			90,000	
Heat (T>200°C)	GJ/a				23,400		
Heat (T<200°C)	GJ/a				15,800		
Wastewater (1 bar, 100°C)	GJ/a	155,000					
Steam	GJ/a	203,000					
District heating (6 bar, 95 °C)	GJ/a					65,000	65,000
Emissions							
Carbon dioxide	t/a					30,000	30,000
Wastewater	t/a	223,000	223,000	223,000		130,000	130,000

⁴ Liebich et al. 2020 also considered cooling water demand in the LCA of the PtG synthesis. However, no cooling water demand is reported in the supplied LCI data. Therefore, no value is specified here.

⁵ Liebich et al. 2020 also considered water produced in the synthesis reaction of PtL and MeOH synthesis. The provided LCI does not specifically mention these water streams in the output section. Therefore, it is assumed that these are allocated to the wastewater stream.



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