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Power-to-Liquids
A scalable and sustainable fuel supply perspective for aviation

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Abstract

The global air transport industry announced the target to achieve net-zero carbon emissions by mid-century. Such a target requires the transition towards renewable fuels, as experts agree commonly. Power-to-Liquids (PtL) offers a credible perspective to produce the required amount of sustainable fuel from abundant sources of renewable electricity and CO_2 from the air. Moreover, PtL has the potential of net-zero carbon emissions of aviation, if produced this way.

The basic concept of PtL was discussed in an earlier version of this report from 2016. This updated version reviews the basic principles of PtL production pathways, discusses the technological readiness achieved to-date, and assesses sustainability aspects vis-à-vis competing fuel options. Furthermore, the technical suitability of PtL fuels as well as substitution and scale-up potentials are summarized, alongside with considerations of PtL cost and economic competitiveness.

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Executive Summary

What is at stake?

Aviation contributes substantially to overall greenhouse gas emissions. To support global efforts towards keeping climate change to a minimum, aviation stakeholders have proposed strategies and industry-specific targets aiming at net-zero emissions by 2050 (ATAG 2021, NLR and SEO 2021). While disruptive aircraft technology minimizing fuel burn or enabling the use of carbon-free fuels, such as hydrogen, may play a vital role in the long run, product cycles for aircraft span over decades, hindering immediate emission reduction via this route.

Hence, renewable and scalable drop-in fuels are key for ensuring a more sustainable future of aviation. In that respect, the ideal option should not only provide near-zero net greenhouse gas emissions but also perform well when it comes to other environmental impacts such as land use or water demand.

What are Power-to-Liquids?

The name Power-to-Liquids (PtL) sketches its production pathway. PtL fuels are produced using electric power as the main source of energy. Water and carbon dioxide represent the principal feedstocks. This general concept is further illustrated in Figure 1.

PtL production includes three fundamental steps:

1. Production of hydrogen via water electrolysis employing renewable electricity
2. Provision of renewable CO_2 and conversion into CO (where needed)
3. Liquid hydrocarbon production and conversion to jet fuel

The synthesis can proceed via the following two pathways:

- Fischer-Tropsch (FT) synthesis and upgrading
- Methanol (MeOH) synthesis and conversion

Like many other kerosene synthesis processes, PtL production yields a mixture of fuel products. This is especially true for the case of Fischer-Tropsch synthesis. The conversion and upgrading processes, however, may be shifted to yield more than 50 % share of jet fuel. The remaining fractions are valuable fuel products as well, which help to decarbonize other sectors like marine or heavy road transportation or serve as feedstock for renewable chemistry.

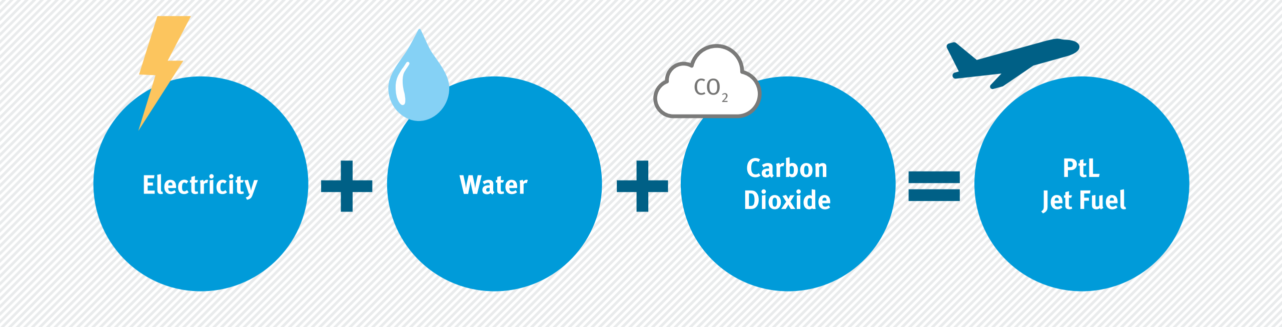
High technology readiness

Both principal PtL pathways introduced above are of high technological maturity. Recently, the first demonstration plant has been inaugurated (Atmosfair 2021) and further projects are underway. Overall, PtL reaches a technological readiness level (TRL) of 5 to 8 on a scale of 1 to 9.

Furthermore, the individual process steps are already well-developed and deployed at large scale: When it comes to the provision of renewable CO_2, concentrated streams from established industrial-scale processes can be used (TRL 9). To gain independence of these so-called "point-sources" and improve the production potential, CO_2 can alternatively be extracted from air (TRL 6-8).

Figure 1

PtL fuel production in a nutshell



Source: LBST/BHL

For the production of renewable hydrogen, water electrolysis is employed. Low-temperature variants such as alkaline or polymer electrolyte membrane electrolysis offer high technological maturity (TRL 9), while high-temperature electrolysis, though less developed (TRL 7-8), can significantly increase process efficiency.

Renewable electricity generation is continuously scaled-up and, at the same time, hybrid solar-wind systems feature higher capacity factors. Moreover, the costs associated with renewable electricity generation continuously dropped over recent years.

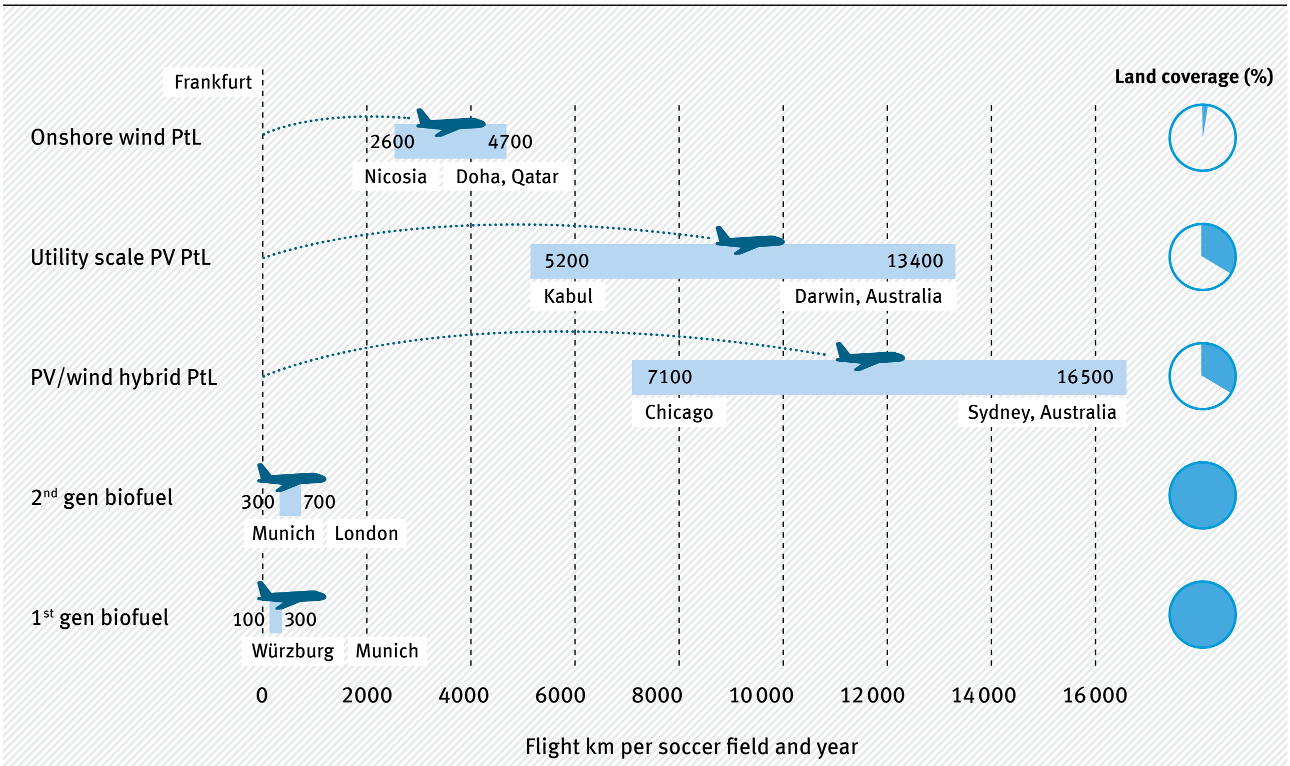
PtL jet fuel is drop-in capable. The ASTM jet fuel standard already allows for a 50 % blend of Fischer-Tropsch synthetic fuel. PtL via the methanol pathway, on the other hand, is not yet approved. Development initiatives have been started, aiming to provide the standardization basis for the use of neat (100 %) Fischer-Tropsch synthetic jet fuel and onboarding the methanol pathway on the roster of ASTM-approved sustainable aviation fuels.

Environmental benefits of PtL

PtL offers a perspective of near carbon-neutral fuel production, when the required feedstocks (CO_2 and H_2O) and the electricity all come from renewable sources. Moreover, both high-altitude climate impacts and local emissions can be reduced as synthetic fuels' combustion is cleaner as kerosene's. Beyond that, PtL fuels are less toxic. Comparing to biomass-based synthetic fuel pathways, on the other hand, PtL is advantageous when it comes to land use and water use. PtL production does not require arable land, moreover, the area demand is dominated by the renewable electricity generation step, solar and wind parks cover land only partially. These stark differences are illustrated in Figures 2 and 3.

Figure 2

Achievable air mileage for an A320neo in km per soccer field* of land and year, and area covered (%)



The land coverage indicates the share of the net area that is covered by renewable electricity generation or crop cultivation.

1st generation biofuels, e.g. HEFA from soybean, jatropha or rapeseed

2nd generation biofuels, e.g. BtL from short-rotation forestry and Fischer-Tropsch synthesis 2nd generation biofuels, proxy: Biomass-to-Liquids (BtL) from short rotation forestry via gasification and Fischer-Tropsch synthesis

* soccer field = 0.71 ha

Source: LBST

The environmental benefits are paramount in PtL jet fuel from renewable sources, lending themselves for successively staggered mass deployment to become a key element in the energy transition of the aviation sector.

Economics and scalability

Compared to conventional jet fuel, PtL suffers from high production costs caused by the multi-step production chain and limited process efficiency. The resulting significant cost difference between kerosene and PtL fuel is a major hurdle for the short-term deployment of PtL. As illustrated above, further developments to specific production steps (high-temperature electrolysis, direct CO_2 capture from air) could enhance the efficiency and, hence, aid to bring down cost. Meanwhile, renewable electricity and electrolyzer cost are continuously declining, and economies of scale are expected to further reduce cost.

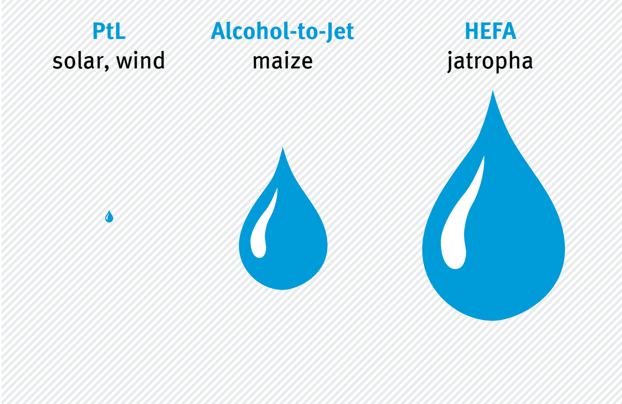
PtL for aviation – A story bright or bleak?

Deploying PtL jet fuel production on a large-scale is associated with certain trade-offs and strategic implications. Figure 4 provides an overview of key strengths, weaknesses, opportunities and threats.

Figure 3

PtL water demand compared to selected biofuels

(Volume representation, PtL water demand 4 $L_{H_2O}/kg_{jet\ fuel}$)



Source: BHL/LBST

Figure 4

Key strengths, weaknesses, opportunities and threats of PtL fuel production

Strengths
- Huge global renewable power potentials
- Drop-in capability (fuel, logistics, propulsion)
- Near-zero GHG emissions potential well-to-wake
- Lower toxicity compared to crude oil-based jet fuel
- Compared to biofuels
  - Lower water demand
  - Lower land requirements

Opportunities
- Clean combustion (low sulfur & aromatic content)
  - Reduction of local air pollutant emissions
  - Reduced high-altitude climate impact
- Strengthening the local economy in regions with large wind and solar power potentials
- Provision of grid ancillary services
- Contribution to hydrogen value chains

Challenges/Weaknesses
- Fuel costs higher than fossil
- Amount of renewable electricity and CO_2 required to substitute jet fuel
- No option for zero pollutant emissions
- Compliance with agreed sustainability criteria (global)

Drawbacks/Threats
- Lock-in of kerosene-based aircraft technologies
- Lock-in of fossil CO_2 sources for synthesis
- Acceptance of large-scale renewable power plant deployment required

Source: LBST/BHL

How could PtL jet fuel be rolled out at scale?

The potential of PtL for significant absolute reductions of the climate and other environmental impacts of aviation has been affirmed. Considering the steep technological progress of recent years and the vast support from various stakeholders, it's no longer a question whether jet fuel production from renewable electricity and CO_2 is feasible. The question is how PtL fuels can be industrialized and mass deployed.

In 2021, the first commercial PtL jet fuel pilot plant was inaugurated. Further projects are in the development phase or announced. The most important requirement for a timely roll-out of PtL fuel production is the creation of a stable demand perspective, which is needed for investment decisions. PtL plant designs need to be further optimized for the utilization of intermittent solar and wind energy resources. In the long-run it is important to develop a sustainable and scalable supply of carbon in form of direct CO_2 extraction from ambient air.

What's next?

- Support accelerated expansion of solar and wind electricity generation capacity to prepare the ground for electricity based fuel production
- Integration of robust, verifiable and reportable sustainability safeguards for renewable PtL jet fuel in existing and upcoming SAF certification systems
- Establish regulations on regional and global level, which ensure stable but consecutively increasing demand for PtL
- Engage in adequate fossil carbon pricing such that the cost gap between fossil and PtL jet fuels converges in the long run
- Standards:
  - Drive PtL technology competitiveness through ASTM approval of PtL jet fuel produced via the methanol pathway
  - Establish appropriate specifications and prepare the ASTM approval of fully synthetic jet fuel
  - Reduce pollutant emissions and non-CO_2 high-altitude climate impacts through allowing for lower and ultimately no aromatic contents in jet fuel
- Establish PtL jet fuel demonstration projects, e.g. with the objective of
  - increasing installed production capacities,
  - improving heat integration, e.g. for high-temperature electrolysis or direct air capture,
  - testing innovative processes for CO_2 extraction from air,
  - fine-tuning conversion / upgrading according to jet fuel specifications, or
  - increasing plant flexibility to operate with high shares of (fluctuating) renewable power sources.

The uptake of renewable drop-in fuels in aviation is an economic challenge. To get to scale, tangible targets need to go hand in hand with supportive measures.

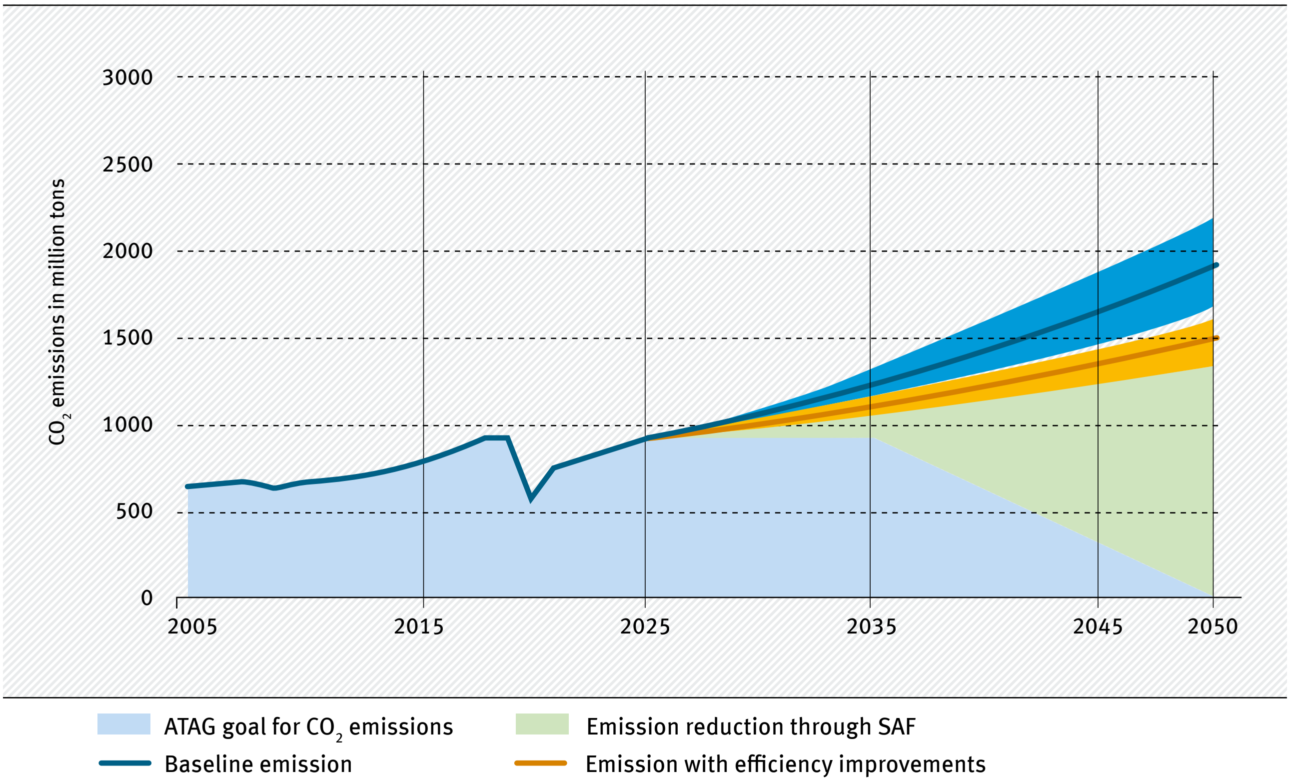
1 An increasing need for renewable fuels in aviation

Human influence on climate change is one of the primary challenges of our times. As the most recent report from the Intergovernmental Panel on Climate Change (IPCC) points out, the last two decades (2001-2020) were roughly 1°C warmer than 1850-1900 (IPCC 2021). Substantial efforts need to be undertaken quickly to implement the Paris Climate Agreement, which aims to limit global warming to well below 2.0°C, preferably 1.5°C, compared to pre-industrial levels. Current commitments through the International Civil Aviation Organization (ICAO) are not aligned with the goals of the Paris agreement (Harvey 2021).

Aviation is one of the most significant polluting industries with 2.4 % of all anthropogenic CO_2 emissions in 2018; in addition, aviation contributes to climate change with impacts from non-CO_2 effects. These effects are likely of the same magnitude or even larger than the CO_2 effect alone. Thus, the full climate impact of aviation is about 5 % of total anthropogenic climate impact (Lee et al. 2021). The industry sees itself more and more under pressure from policy makers, financial investors and civil society to substantially reduce its climate impact. In turn, aviation stakeholders are developing strategies how to become carbon neutral by mid-century. Two much-noticed reports, “Destination 2050” and “Waypoint 2050”, released by the European aviation industry (NLR and SEO 2021) and the Air Transport Action Group (ATAG 2021), respectively, sketch perspectives to achieve carbon neutral aviation by 2050 in Europe and worldwide. Most recently, the International Air Transport Association (IATA) agreed to achieve net-zero carbon emissions by 2050 (IATA 2021). In all cases, sustainable aviation fuels (SAF), which can substitute conventional jet fuel within the existing fleet of aircraft account for the bulk part of

Figure 5

Possible long-term development of aviation CO_2 emissions



Possible long-term development of aviation CO_2 emissions. Baseline emissions reflect demand growth at constant technology assumptions (dark blue) and under a scenario with efficiency improvements due to evolutionary aircraft technology development and operational improvements (orange). Considering the CO_2 emission reduction targets according to ATAG 2021 (light blue), the emissions gap between light blue and orange would need to be covered with SAFs. Note that the climate impact of aviation through non-CO_2 effects are not covered in this figure.

the transition. Here, Power-to-Liquid (PtL) fuels could play a particularly important role, as large volumes of truly sustainable fuels will be needed to grant a "licence to operate" to the aviation sector in a carbon neutral future. Furthermore, to address the full climate impact of aviation, it is necessary to reduce non-CO_2 effects alongside with carbon neutrality. The combustion of synthetic fuels emits less soot, which mitigates the climate impact of aviation induced clouds at high altitudes. However, the transition to carbon neutral and cleaner burning fuels still needs to go in hand with improved aircraft engines and operational measures to drastically reduce the climate impact at high altitude.

1.1 Future demand for air travel and sustainable fuels

The aim to make aviation climate neutral is additionally challenging because of the sustained increase in air travel demand. Between 2010 and 2019, air travel grew by slightly more than 5 % per year. During the unprecedented shock due to the COVID-19 pandemic, air travel collapsed and is expected to reach 2019 demand levels again by around 2025 (ATAG 2021). Assuming a return to a continued growth path of around 3 % on average per year after 2025 results in an air travel demand which is slightly more than twice as high in 2050 as in 2019 (ATAG 2021). As the European market is already mature, air travel growth is expected to grow at a slower pace in the EU compared to the global average (Giannelos et al. 2021).

Growing air travel demand does not directly translate into a fuel demand growth with the same pace, as aircraft fleets and operational procedures have continuously become more fuel-efficient. Regarding operational procedures, improved air traffic management (such as more direct routing of aircraft, less air space congestion, electric taxiing, etc.) and higher seat load factors could lead to a long-term fuel burn reduction of up to 10 %. With respect to aircraft fuel burn, historical trends of efficiency improvements are expected to continue (Kharina and Rutherford 2015), but at a slightly lower pace of slightly below 1 % per year. This would result in a relative, fleet-wide fuel burn reduction of around 20 % in the next 30 years if evolutionary technologies are considered. Battery electric flying is only viable on short ranges, as it is limited by the energy density of batteries. Hydrogen aircraft concepts are discussed as a potential long-term option, but their development would likely take around 15 years until market maturity and involves considerable technological challenges. This is why we do not explicitly consider these more revolutionary technologies here and rather take a conservative approach regarding aircraft technologies.

Taking both air travel demand increase (post-COVID) and efficiency improvements into consideration, global demand for kerosene could increase from 294 Mt in 2019 to 430-530 Mt in 2050. For Europe, fuel demand could increase from 49 Mt in 2019 to 55-70 Mt in 2050.

Despite the considerable uncertainties involved with predictions of air travel demand after the COVID-19 pandemic, most experts agree on a net fuel demand increase, which would in turn lead to a substantial growth of greenhouse gas (GHG) emissions instead of a targeted reduction. Consequently, it is necessary to shift fuel use from fossil to renewable. Future large-scale use of renewable energy carriers is considered as an essential pillar to close this so-called "emissions gap".

1.2 PtL offers a robust option within existing fleets and infrastructures

Drop-in capable alternative fuels, in other words synthetic kerosenes, offer a number of advantageous properties, in particular the combination of high energy density (energy per volume) and specific energy (energy per mass) in comparison to other options being discussed. Furthermore, drop-in fuels can be distributed and used within existing infrastructures alongside conventional jet fuel.

Consequently, current efforts in research, industrial development and deployment are focused on renewable drop-in replacements for conventional jet fuel. The European Commission, too, repeated its aim to support the switch from fossil to sustainable kerosene, and specified its strategy in the "ReFuelEU Aviation" Initiative (European Commission 2021). These efforts have resulted in an increasingly broad and diverse landscape of production pathways towards alternative liquid fuels.

In the context of the tremendous challenge of substantially reducing the environmental footprint of aviation, SAFs need to offer

- highly reduced specific GHG emissions on a lifecycle basis,
- reduced air pollutant emissions,
- lower climate impact from aviation induced cloudiness,
- low footprint regarding water and land consumption,
- large production potentials.

PtL fuels, i.e. fuels produced with electricity, water, and carbon dioxide from renewable sources, have the potential to offer these advantages. In 2016, the UBA background paper "Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel" (UBA 2016) provided an overview of the emerging PtL technology. Within the last five years since its publication, technological improvements, economic framework conditions, and public discussion around PtL deployment made substantial progress. Consequently, this publication has the aim to give an overview of the actual state of the art, and update the previous report regarding the major fields of development.

In the following sections, the fundamental technical principles of the PtL technology are laid out and the actual state and bottlenecks of development are discussed. Furthermore, PtL fuels are set into context with other production technologies for renewable jet fuels, and main conclusions are formulated.

2 Power-to-Liquids: The basic principles

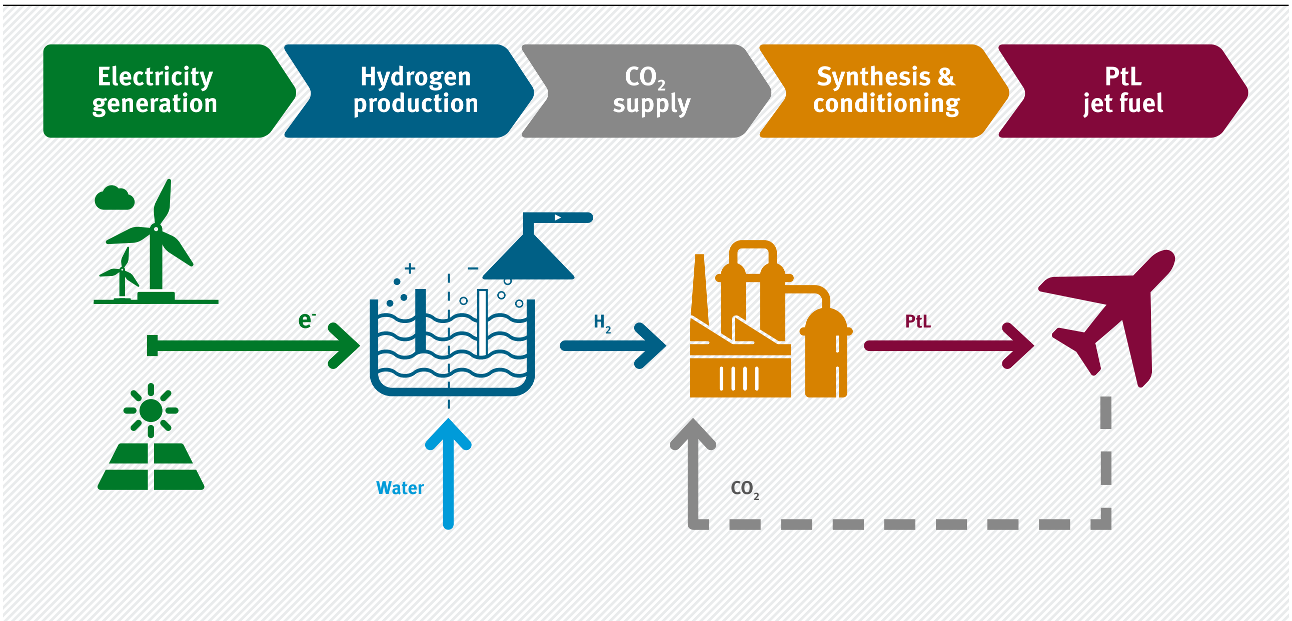
2.1 How liquid fuels are made from renewable power

Sharply falling electricity generation cost from solar and wind energy raised massive attention to the concept of PtL over the last years. Numerous scientific publications, reports and scenario analyses have been published on this subject, including the initial version of this background paper from UBA (2016). Among policy makers (Bundesregierung 2021, European Commission 2021) and the aviation industry, it is increasingly acknowledged that fuels from renewable electricity can play a major role to achieve carbon neutrality (ATAG 2021). Within this section, the basic technologies for the most common PtL fuel production pathways are reviewed.

Figure 6 sketches a generic scheme of PtL jet fuel production from the main constituents renewable

Figure 6

Power-to-liquids production (generic scheme)



Source: LBST

electricity, water and carbon dioxide (CO_2). Renewable electricity is predominantly produced from solar and wind power to meet the scale of future jet fuel demand. The main energy conversion step from renewable power to chemical energy carriers is achieved by means of water electrolysis. In the following, liquid hydrocarbon fuels are synthesized from electrolysis hydrogen and carbon dioxide.

Important design options for PtL pathways include the electrolysis technology and the source of CO_2. The most common conversion pathways for liquid fuel synthesis are the Fischer-Tropsch (FT) pathway and the methanol (MeOH) pathway. The different design options are discussed in more detail in the following.

Excursion – Terminologies for electricity-derived fuels

Consistent sets of terminologies for electricity-derived fuels have been proposed, e.g. by Bünger et al. (2017). A single common taxonomy, however, has not yet been established. The terms 'PtL', 'powerfuel', 'e-fuels', 'e-kerosene', 'renewable fuels of non-biomass origin' (RFNBO), or simply 'synthetic fuel' are often used synonymously. The terms 'e-fuel', 'powerfuel' and 'RFNBO' clearly include hydrogen as a fuel option, while e-kerosene refers to only one product from PtL processes, whereas 'synthetic fuel' also applies to FT fuels from biomass, natural gas or coal and further synthetic fuel pathways. The term PtL is sometimes applied to other electricity-derived fuels, which are liquid at room temperature such as methanol. Within this report PtL is understood as a pathway that yields a large fraction of kerosene range hydrocarbons with similar chemical and physical properties as conventional jet fuel.

Electrolyzer technologies

Power-to-hydrogen options include alkaline electrolyzer, polymer electrolyte membrane (PEM) electrolyzer, and solid-oxide electrolysis cells (SOEC). High-temperature electrolysis (e.g. SOEC) can significantly reduce the electricity demand compared to low-temperature electrolysis (alkaline, PEM). This can result in an overall benefit at system level when suitable heat sources, such as waste heat from the exothermic Fischer-Tropsch synthesis, are available for steam generation. On the other hand, alkaline and PEM electrolyzers provide benefits in terms of (current) system costs, durability and load flexible operation[1]. Therefore, low-temperature electrolysis may be regarded as baseline technology at the current state of art.

Renewable electricity from solar and wind generates a fluctuating power profile, while continuous operation is beneficial for fuel synthesis. Thus, PtL plants will most likely involve hydrogen storage as a buffer for short-term fluctuations. Established hydrogen storage options include pressure vessels, storage pipes, and salt caverns. For longer time-scales it will be subject to techno-economic plant optimization whether hydrogen is stored or if downstream conversion steps get designed for load flexible operation.

CO_2 sources

Industrial CO_2 is currently supplied from various sources, in many cases it is generated as a by-product of industrial processes. Important sources of concentrated CO_2 can be of renewable as well as of fossil origin (see Section 3.3). The mode of CO_2 supply has profound consequences on the scalability as well as the economic and environmental viability of PtL schemes. It is clear that only renewable CO_2 sources can produce a truly carbon-neutral fuel in the long run. Due to scale-considerations, it is an important perspective to extract CO_2 from the atmosphere via direct air capture (DAC) technologies, thereby closing the carbon cycle.

CO_2 is inert and can be stored in liquefied form; considerations for buffer storage at the plant site are similar to H_2 storage, but storage costs are lower. However, transport of CO_2 is a logistic challenge that needs to be addressed for each individual PtL plant, which is not co-located with a suitable CO_2 source.

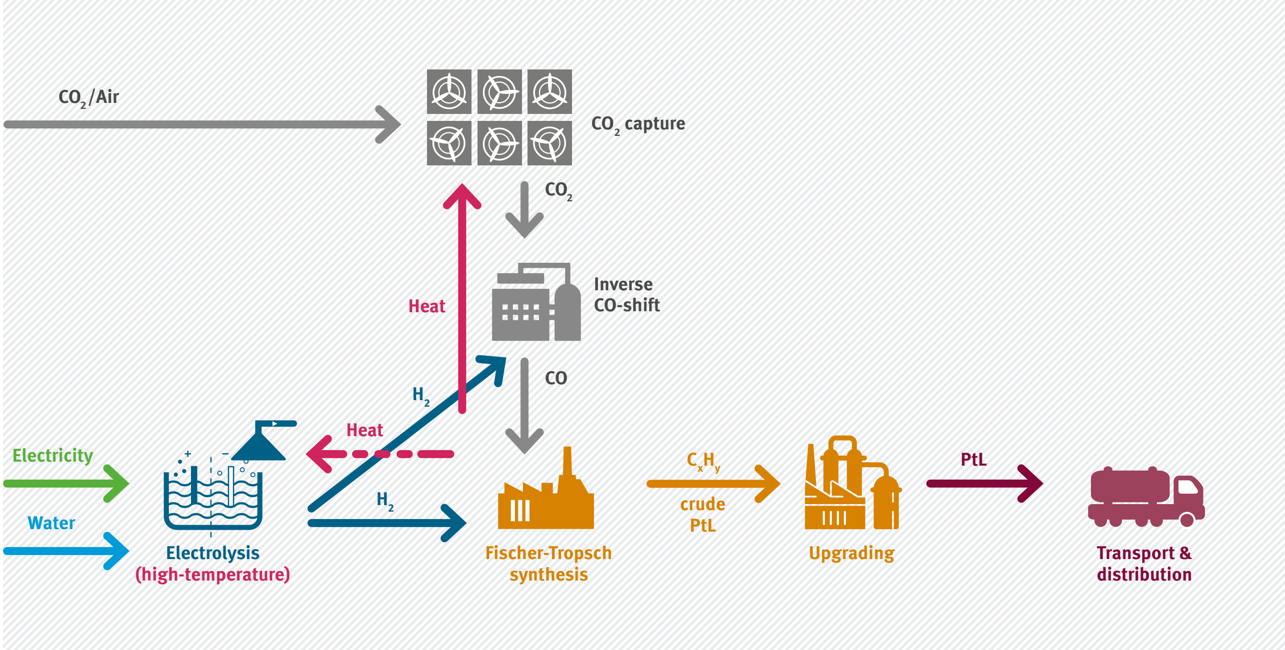
Fischer-Tropsch pathway

Fischer-Tropsch fuels are already produced from natural gas and coal reserves. The technologies for

1 Single electrolyzer stacks have a typical capacity of a few MW, while typical PtL plants will be much larger (> 100 MW). Optimum plant designs may therefore benefit from different electrolysis technologies.

Figure 7

PtL production via Fischer-Tropsch pathway (high-temperature electrolysis optional)



Source: LBST

large-scale gas-to-liquid (GtL) and coal-to-liquid (CtL) processes are fully developed, including upgrading and refinement steps. Established approval processes allow the use of Fischer-Tropsch fuels in civil aviation. Fischer-Tropsch synthesis requires hydrogen and carbon monoxide at a ratio of about 2:1 as a feed stream; this gas mixture is usually termed synthesis gas. Instead of natural gas reforming or coal gasification, synthesis gas can be derived from biomass gasification (biomass-to-liquid, BtL) or from water electrolysis and CO_2 (PtL, see Figure 7). In the PtL case, a fraction of the H_2 stream from water electrolysis is reacted with CO_2 to obtain CO via the reverse water-gas shift reaction (RWGS).

Fischer-Tropsch synthesis evolves via chain growth reactions. The resulting product contains a mixture of linear hydrocarbons which is not yet suitable as jet fuel. Further process steps, notably hydrocracking, isomerization, and distillation are necessary to produce finished fuels. Several options to use Fischer-Tropsch fuels in civil aviation are already approved, see Section 2.2 for more detail.

Methanol pathway

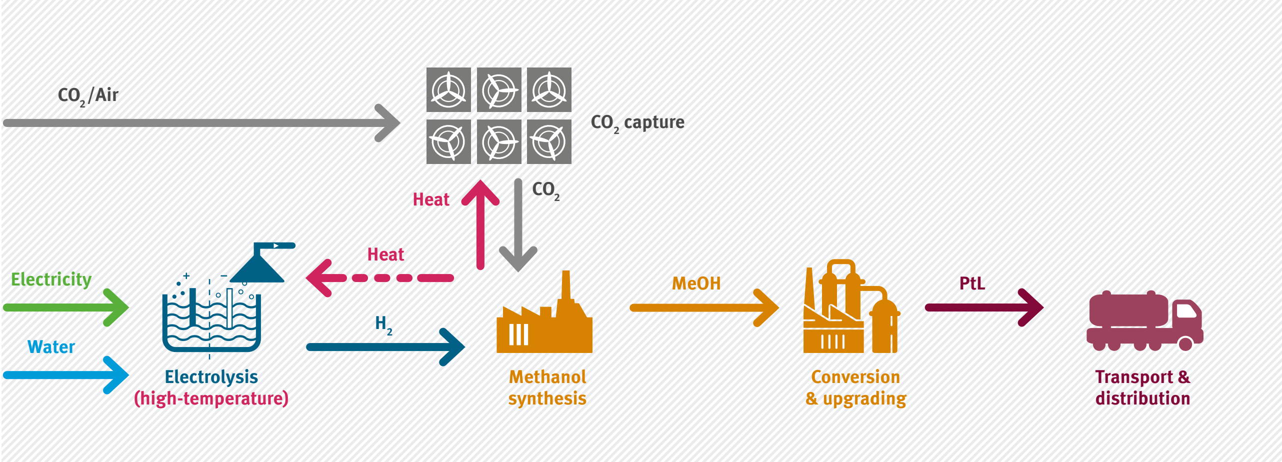
An alternative pathway for the production of liquid hydrocarbons, including jet fuel, is via the intermediate product methanol. The pathway can also build on industrially proven processes, which were used for decades in various large-scale applications. The methanol pathway towards jet fuel is depicted in Figure 8, again heat from exothermic synthesis steps can be used for high-temperature electrolysis or CO_2 capture.

Current large-scale installations for methanol synthesis utilize H_2, CO and CO_2 from natural gas reforming or coal gasification. However, methanol can also be directly synthesized from H_2 and CO_2, an additional process step for CO generation is not necessary in that case.

Conversion and upgrading of methanol to jet fuel comprises several process steps, notably olefin synthesis, oligomerization, and hydrotreating. The basic process steps are already used at large-scale in refineries and chemical plants today. However, jet fuel is not yet commercially produced via the methanol pathway and an approval to use of methanol based fuels in aviation is pending.

Figure 8

PtL production via methanol pathway (high-temperature electrolysis optional)



Source: LBST

Considerations for PtL refineries

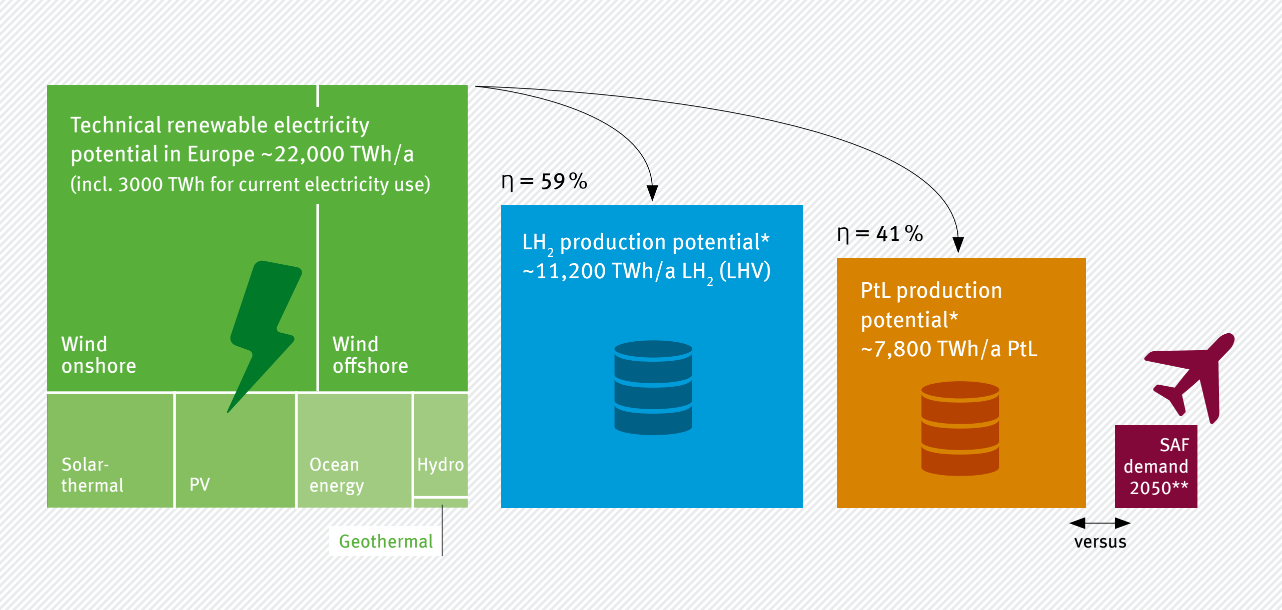
Similar to crude oil refineries, future PtL refineries and their value chains are expected to serve various purposes. The Fischer-Tropsch pathway can yield very different product portfolios depending on the specific technology choices for Fischer-Tropsch synthesis and refining steps. Existing FT facilities tend to focus on diesel production due to current market conditions. Adapted process steps can yield 50-60 % jet fuel at the expense of diesel output. Naphtha, a feedstock for renewable chemistries, may then become the main by-product. Methanol-based synthesis processes may be even more selective towards jet fuel. Furthermore, methanol itself is a potential fuel for the road and maritime sector as well as a platform molecule for renewable chemistry. The option to transport methanol and synthesize fuels elsewhere is an important perspective for the methanol pathway. The tremendous amount of electricity that is needed suggests that PtL plants will also become an important factor within electricity systems.

Renewable power potentials

The technical production potential from renewable electricity sources in Europe is derived from a meta-analysis of available studies and complemented with own calculations. In the literature, different kinds of technical potentials have been assessed, for example: technical-social or technical-economic potentials. Technical potential defines the amount of renewable electricity that can be produced in a region given technological restrictions, typically also taking exclusion areas (natural habitat, protected areas, built environment, etc.) into account. There is, however, no unified methodology across the various studies. The different definitions and assumptions applied lead to a bandwidth of results, which are depicted in Figure 15 in Annex 7.1. A best estimate thereof is depicted in Figure 9 for Europe with 22,000 TWh/a. This compares to an electricity demand of 1690 TWh/a assuming that the European jet fuel demand of 63 Mt/a in 2050 (average of the bandwidth described in Section 1) is completely covered by PtL. Total technical renewable power production potentials for Germany and at global scale are in the order of 1,000 TWh/a and 1,350,000 TWh/a, respectively.

Figure 9

Renewable power potentials and potential SAF demand in 2050 in Europe



η = conversion efficiency

* Excluding 3000 TWh/a current electricity use

** Best estimate of 2050 EU national and international flights (63 Mt/a) assumed as PtL (760 TWh/a)

Source: LBST

2.2 Drop-in capability of PtL fuels

Safety is of highest importance in aviation. Consequently, rigid national and international standard specifications apply to ensure safe operation. Historically, various types of liquid hydrocarbon fuels were used in aviation, due to their availability and high energy density at ambient temperatures. Today, civil aviation relies almost exclusively on a single type of kerosene-range turbine fuel, due to the superior performance of gas turbines for large aircraft[2] and due to considerations of safe operation in various climatic conditions (Chevron 2006).

The most relevant specifications for crude oil-derived jet fuels are listed in ASTM D1655. The basic physical and chemical properties of synthetic fuel alternatives are similar to conventional jet fuel, but the specific molecular composition of synthetic kerosenes can be substantially different. In turn, adapted specifications are necessary. For civil aviation, seven different types of synthetic kerosene[3] are approved as a blend component to conventional jet fuel according to the ASTM D7566 standard specification. The philosophy behind ASTM D7566 foresees a specific set of specifications for each synthetic kerosene production pathway. These batch requirements need to be met by the synthetic blend components. In addition, a common set of specifications applies to all finished fuel blends. This strategy reflects properties of the individual synthetic fuel options on one hand, and ensures on the other hand that the final blends can be safely used as a turbine fuel in the existing fleet of aircraft just as conventional jet fuels.

Specifications for Fischer-Tropsch fuels

For the Fischer-Tropsch pathway, the most relevant D7566 specification for power-to-liquid fuels are Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene (FT-SPK)[4]. FT-SPK was the first type of synthetic fuel that has been approved according to ASTM D7566 in 2009. Since then up to 50 % FT-SPK can be used in blends with conventional jet fuel, as

2 Piston engines, which are common in general aviation, require aviation gasoline (or diesel in few cases). Gas turbines are more tolerant regarding fuel composition, which gives room to adapt fuel specifications according to other important aspects of operation.
3 As of September 2021
4 "Synthetic paraffinic kerosene" describes a mixture of n- and iso-alkanes. In contrast to conventional jet fuel SPK does not contain appreciable amounts of cycloalkanes or aromatics.

long as iron or cobalt catalysts are used for FT synthesis and subsequent hydroprocessing steps ensure that specifications are met. More recently, FT Synthesized Paraffinic Kerosene plus Aromatics (FT SPK/A) was approved, which describes a mixture of FT-SPK with synthesized aromatics.

Another important option to introduce Fischer-Tropsch products into aviation is co-processing in specific units of conventional refineries with a co-feeding ratio of up to 5 %. The upgrading steps, which are necessary to produce FT-SPK are not needed in this case. Instead, the raw product of Fischer-Tropsch synthesis (a synthetic crude), can be fed into an existing refinery.

Specifications of methanol based fuels

PtL jet fuels which are synthesized via the methanol route are not yet approved for civil aviation. Methanol is an alcohol that contains only one carbon atom per molecule (C1). When produced from ethanol (C2) or isobutanol (C4), Alcohol-to-Jet Synthetic Kerosene (ATJ-SPK) is approved as a blending component of up to 50 % with conventional jet fuel. ATJ-SPK blending components are defined as hydroprocessed synthesized paraffinic kerosene through dehydration, oligomerization, hydrogenation and fractionation. It is planned to extent the approved feedstock for ATJ-SPK to all C2-C5 alcohols[5]. Despite similarities, methanol is not listed as intended future feedstock for ATJ-SPK. Considering the good physicochemical properties however, it is likely that PtL produced via the methanol pathway will get a separate specification.

Table 1

Selection of relevant specifications for the use of PtL products in civil aviation

Pathway	Standard	Max. blend rate	Aromatic content	Fleet compatibility
FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene)	ASTM D7566 Annex A1	50 %	‹ 0.5 %	Only in blends
FT-SPK/A (FT-SPK with aromatics)	ASTM D7566 Annex A4	50 %	‹ 20 %	Potentially fully compatible
ATJ-SPK (Alcohol-to-Jet SPK)	ASTM D7566 Annex A5	50 %	‹ 0.5 %	Only in blends
Finished blends with conventional jet fuel	ASTM D7566	-	8 – 25 %	Fully compatible
Co-refining of FT synthetic crude	ASTM D1655 Annex A1.2.2	5 % (co-feeding ratio)	not defined	Fully compatible
SASOL fully synthetic fuel	ASTM D1655 DEF STAN 91-91	100 %	8 – 25 %	Fully compatible
Methanol pathway	Future	Target: 50 – 100 %	Subject to pathway design	Potentially fully compatible
Fully synthetic jet fuel	Future	Target: 100 %	Few %	Fully compatible
100 % SPK jet fuel	Future	Target: 100 %	Well below 1 %	Compatible with advanced aircraft

5 C2-C5 alcohols can also be synthesized from H_2 and CO_2 but the methanol route seems more reasonable

The road towards 100 % synthetic jet fuel

The current share of synthetic aviation fuel is still very low (< 1 % in 2020). A maximum blending rate of 50 % synthetic kerosene with 50 % crude oil-derived jet fuel may be regarded as sufficient for the near-term future, but it is clear that this “blend wall” needs to be overcome, as it is in conflict with the long-term climate targets of the aviation industry. The 50 % blend wall is not a physics-based limitation, as somewhat higher blend levels could be acceptable in the future (J. Holladay, Z. Abdullah, J. Heyne 2020). Two basic strategies are currently discussed for the future use of fully synthetic jet fuel: (i) The approval of 100 % synthetic fuels that resemble all important properties of conventional jet fuel. Such ‘drop-in’ fuels offer the advantage of being compatible with the existing fleet of transport aircraft. (ii) Adapting the fuel systems of new-built aircraft to tolerate 100 % synthetic kerosenes, which slightly deviate from conventional jet fuel specifications. 100 % SPK jet fuel is not compatible with many existing aircraft, but offers important benefits in the long term.

In fact, the use of a fully synthetic jet fuel is already approved and first flights took place in 2010[6]. This peculiarity dates back to the development of Fischer-Tropsch fuels from coal reserves in South Africa, so far, the existing approval applies only to a specific coal-to-liquids facility. Nevertheless, it may serve as a blueprint to develop more general specifications for 100 % synthetic drop-in fuels that achieve fleet-wide compatibility by blending appropriate synthetic streams until all relevant properties of conventional jet fuel are met. One pivotal aspect of fully synthetic jet fuel is the intentional increase in aromatic content, as a certain level of aromatics is needed to ensure full compatibility with the existing fleet of aircraft[7]. The approval of FT-SPK/A prepares the ground for fleet-wide compatible fully synthetic fuels.

SPK in its neat form offers a number of important advantages compared to synthetic fuels that mimic the properties of conventional jet fuel, including a slightly higher specific energy density and a significant reduction in soot formation. Both benefits are linked to the low aromatic content. Due to these profound benefits, the aviation industry is adapting the fuel systems of future aircraft to fully synthetic fuels like SPK in their neat form. Such an adaption at the aircraft level allows to take full advantage of the superior properties of synthetic fuels, especially with regard to improved air quality and reduced high-altitude climate impact. However, during a transition period, separate fuel infrastructures may be required at airports.

3 Technical, economic, and environmental aspects of Power-to-Liquids

3.1 Technological maturity of Power-to-Liquids production

Table 2 gives an overview over the technological maturity of renewable fuel production pathways using the concept of ‘Technology Readiness Levels’ (TRL). The scale of TRL reaches from 1 to 9, (see Table 10 in Annex 7.2). All individual process steps along power-to-liquid pathways offer a high level of technological maturity. Recently, first proof-of-concept plants that integrate PtL value chains, from renewable electricity and CO_2 to readily marketable products are under development. Such proof-of-concept plants are important to provide certainty to planners, users, and investors.

6 Sasol takes to the skies with the world’s first fully synthetic jet fuel, press release 22.9.2010, www.sasol.com/media-centre/media-releases/
7 Aromatics interact with elastomers in fuel systems (seal swell)

Table 2

Current Technology Readiness Levels (TRL) of production pathways to renewable jet fuel

Jet fuel production pathway	Technology Readiness Level (today)	Critical technical element (e.g. determining bandwidth bottom)
PtL	**5 – 8**	**CO_2 extraction from air, co-SOEC**
Fischer-Tropsch (low-temp)	7	Large-scale reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5 – 6	High-temperature electrolysis (co-SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	7 – 8	SOEC, ASTM approval, final conversion
BtL		
Lignocellulosic biomass	7	Feedstock quality
HEFA	**4 – 9**	**Algae feedstock**
Rape seed, soy, used cooking oil	9	
Algae	4 – 5	Algae cultivation, extraction
AtJ	**7 – 9**	**Conversion**
Sugar & starch	8 – 9	AtJ process
Lignocellulosic biomass	7 – 8	Conversion

HEFA – Hydroproccessed Esters and Fatty Acids, AtJ – Alcohol-to-Jet fuel

Source: LBST

The high level of maturity of Fischer-Tropsch conversion technologies stems from large-scale coal-to-liquids (CtL) and gas-to-liquids (GtL) plants. The technology needs to be adapted towards smaller scale and for more flexible operation in case of PtL. Furthermore, additional process steps like CO_2 conversion to CO via reversed water gas shift are not needed in CtL and GtL and require demonstration at scale.

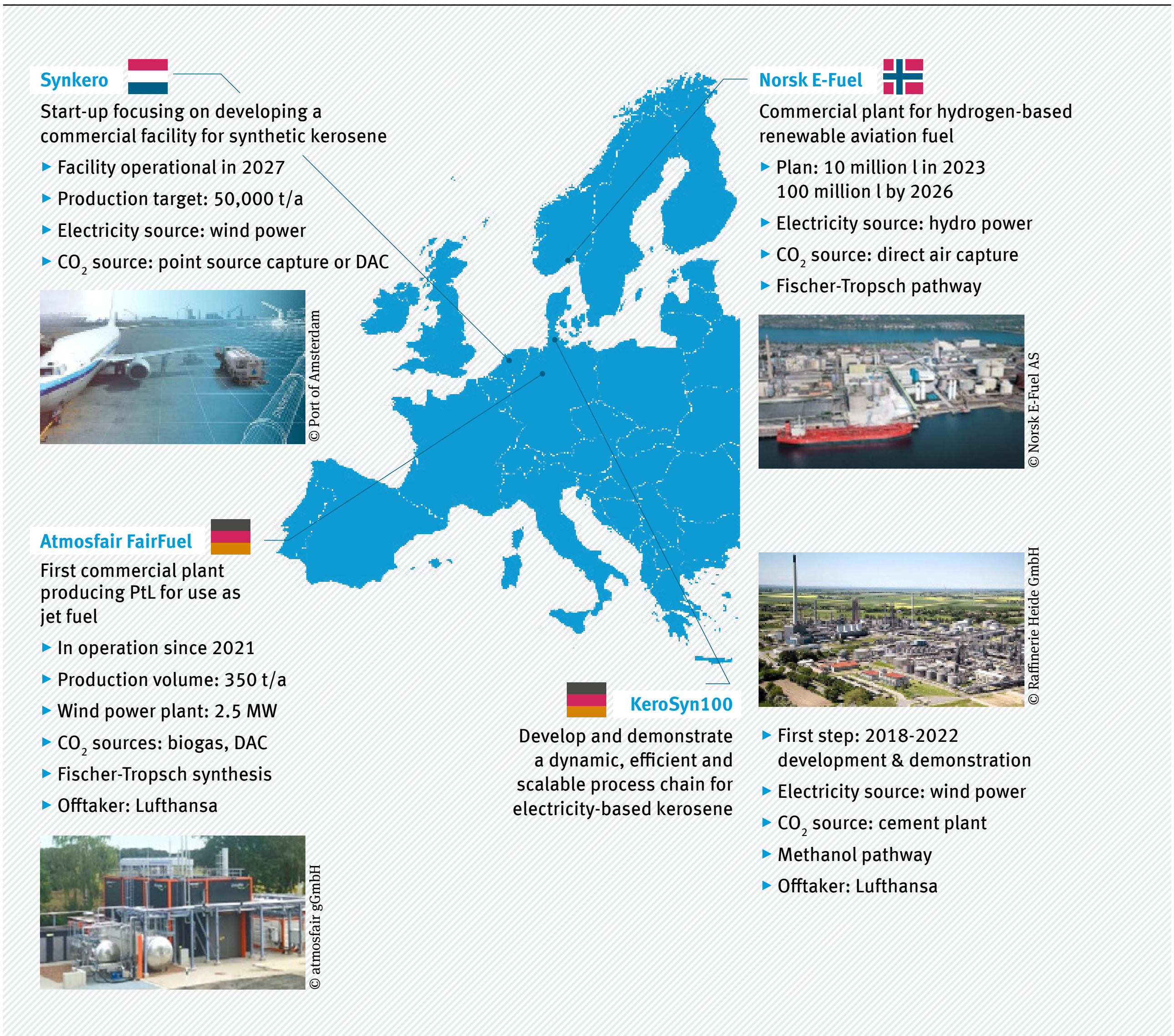
For the downstream processing of methanol, integrated methanol-to-gasoline plants are commercially available. All components for the methanol-to-olefin conversion and subsequent upgrading are proven in conventional refinery processes (see Table 11 in Annex 7.2). However, an integrated process chain for the purpose of middle-distillate (diesel, jet fuel) production has not yet been demonstrated.

Regarding technologies for water electrolysis, alkaline electrolyzers have been used for many decades in various industrial applications (TRL 9). Polymer membrane electrolysis began market introduction (TRL 9). Emerging electrolyzer technologies (solid-oxide electrolysis, TRL 7-8 for water electrolysis and TRL 5-6 for co-electrolysis) still need major technological progress. In light of numerous hydrogen strategies all over the world, electrolyzer manufacturers are stepping up production capacities and development pace for established and emerging electrolyzer technologies, respectively.

For the supply of CO_2, different sources and processes are available, ranging from conventional scrubbing processes and pressure swing adsorption for CO_2 extraction from biogas upgrading (TRL 9) to vacuum temperature-swing absorption processes for CO_2 extraction from air (both TRL 7-8) or novel electro-dialysis (TRL 6). Besides process development for the extraction of CO_2 from air, production capacities need to be scaled-up as this CO_2 supply option is required at least for bulk PtL production in the long-run or even before.

Figure 10

Exemplary PtL projects in Europe



DAC = direct air capture

Source: LBST

PtL plants and projects

Recently, the first demonstration plant for the production of power to kerosene has been inaugurated in Werlte (Germany) (atmosfair 2021). The facility produces about 350 t of Fischer-Tropsch synthetic crude per year, which is processed further to kerosene at the Heide refinery (Germany). The concept comprises a low temperature PEM electrolyzer. The electricity is derived from a wind farm and the CO_2 is partly derived from biogas upgrading and partly from direct air capture (DAC). Figure 10 gives a few examples of PtL projects underway in Europe.

3.2 Energy efforts (efficiencies)

Table 3 depicts the efficiency of the production of PtL, differentiated by the CO_2 source and the synthesis technology applied.

As can be seen from the table, two parameters are significantly influencing the energy efficiency of PtL production 'well-to-tank': the CO_2 source and the synthesis technology. If a concentrated source of CO_2 is available – such as biogas upgrading or exhaust gas streams of wood burning for combined heat and power production – the energy efficiency is some 10 %-points higher compared to PtL production with CO_2 extraction from the air. However, sources of concentrated CO_2 might be limited in light of cross sectoral climate protection and sustainability measures. Using the methanol pathway may improve energy efficiency by another 3 to 6 %-points compared to the Fischer-Tropsch pathway employing low-temperature electrolysis depending on the CO_2 source.

The long-term energy efficiencies of PtL production pathways investigated in this study can be as low as 42 % and as high as 57 % 'well-to-tank', subject to the combination of CO_2 source and synthesis technology.

The methanol requirement is based on data for an existing power-to-methanol plant (George Olah in Iceland), which is fully integrated up to the point of methanol provision. The hydrogen requirement is indicated with 0.193 kg H_2 per kg of methanol leading to about 1.16 MJ per MJ of methanol related to the lower heating value (Stefansson 2015).

The energy conversion efficiency has a direct impact on the required electricity demand for PtL fuel production, and therefore on the process economics and the acceptance of large scale solar and wind energy deployment. Nevertheless, further key performance indicators may be more relevant than energy conversion efficiency to highlight the advantages of PtL fuel production from renewable electricity in comparison to other fuel options.

3.3 Greenhouse gas emissions

Power-to-liquids from renewable sources can provide deep reductions in greenhouse gas emissions per unit of fuel, which is a necessary feature for sustainable aviation fuels with a long-term perspective. According to to LBST (2016) and JEC (2020) the overall greenhouse gas emissions for production, transportation, distribution and dispensing of PtL from electricity and CO_2 from renewable sources are about 1 g CO_2 equivalent per MJ of final fuel. Since renewable electricity and CO_2 are used for jet fuel production, direct greenhouse gas emissions[8] only occur at

Table 3

PtL production efficiencies 'gate-to-gate' (fuel output vs. electricity input)

Pathway	PtL production efficiency today ⟶ improved, using CO_2 from different sources	
	CO_2 from air (~410 ppm)	Concentrated CO_2 source (45 vol-%)
Methanol pathway	41 % ⟶ 45 %	50 % ⟶ 57 %
Fischer-Tropsch pathway	37 % ⟶ 42 %	45 % ⟶ 51 %

Source: LBST (based on Soler & Schmidt 2021)

8 Carbon footprint accounting as stipulated in the recast of the Renewable Energy Directive (European Commission 2018) and according to JEC (2020), i.e. without GHG emissions from asset construction (power plants, fuel production facilities, etc.) and without non-CO_2 high-altitude climate impacts, respectively.

transportation, distribution and dispensing. Including the construction of power stations and the PtL plant the greenhouse gas emissions for the production of PtL amount to 5 to 10 g CO_2 equivalent per MJ of final fuel when using electricity from offshore wind in Norway and wind/PV hybrid power stations in Germany, respectively, according to a recent life-cycle assessment of jet fuel production via power-to-liquids (Soler & Schmidt 2021). In that study, low temperature (alkaline) electrolysis with downstream Fischer-Tropsch synthesis and upgrading as well as CO_2 extracted from a mix of CO_2 sources (concentrated CO_2 sources, direct air capture) using waste heat has been assumed. The life-cycle impact of the construction of PtL facilities, as well as PV and wind power plants, will decrease in the future due to technological improvements and an ongoing decarbonization of energy and materials.

The CO_2 source is also important for the greenhouse gas balance of PtL. Today, i.e. early in the deployment phase with the very high production costs that come with the initially small production capacities, industry stakeholders are looking for the most concentrated CO_2 sources available in the short-term to save on process energy demands, reduce plant complexity, and lower asset investments. However, there are clearly different levels of (un)sustainability that come with the different CO_2 sources, i.e. direct atmospheric, indirect atmospheric, non-avoidable, and avoidable CO_2 sources. Some examples for CO_2 sources that are regularly referred to in discussions are depicted in Table 4. What 'un-avoidable' means in the context of CO_2 quantities available from different CO_2 sources is in fact a soft indicator and moving target. The level of 'unavoidability' changes with technology developments (e.g. direct iron ore reduction using hydrogen), appreciation of potential substitutes (e.g. wood instead of concrete), or direct avoidance (e.g. changing consumption patterns).

Table 4

Sustainability aspects of exemplary CO_2 sources

CO_2 sources	Environmental sustainability	Alternative CO_2 uses	Towards carbon-neutrality; Risks
Extraction from air	Subject to electricity source		
Biogas upgrading	Subject to feedstock & process	Power-to-methane	Other land or sustainable biomass uses; LULUCF
Solid biomass fired heat (& power) plants	Subject to feedstock & process	Bio-CCS	Other land or sustainable biomass uses; LULUCF
Fermentation to alcohols	Subject to feedstock & process	Beverage industry	Other land or sustainable biomass uses; LULUCF
Geothermal sources	Subject to geo-phys. CO_2 cycle	CO_2 re-injection (closed loop)	Hot dry rock a potential no-go
Cement, burnt lime or glass production	Short-term exemptions?	Power-to-chemicals	Shift to alternative materials, recycling; Technology lock-in
Steel production	Short-term exemptions?	Top-gas for heating & reduction	Shift to direct reduction with H_2
Fossil fuel firing	Short-term exemptions?	CCS	Phase-out; Technology lock-in

CCS = Carbon capture & storage; H_2 = Hydrogen; LULUCF = Land use, land-use change, and forestry

Source: LBST

CO_2 from fossil sources is not sustainable. In some cases though, subject to GHG allocation or regulatory rules, the use of CO_2 from fossil sources is discussed for hydrocarbon synthesis. Sustainability safeguards are necessary to avoid unintended collateral damages, such as lock-in of fossil technologies and carbon leakage into unregulated sectors. From today's perspective, direct capture of CO_2 from air (DAC) using renewable energy is the only sustainable CO_2 source at scale and long-term availability. The sustainability of using CO_2 from biogas upgrading or fermentation to alcohols, and exhaust gas CO_2 from biomass fueled heat and power plants can be assumed for biogenic co-products, residues or waste streams. These feedstock may not classify as 'sustainable' if these are based on unsustainable practices or its use is deterring the introduction of more circular resource uses.

In case of CO_2 from geothermal plants it is subject to the geo-physical cycle. A closed water loop including re-injection of the CO_2 can avoid these CO_2 emissions. In case of cement, burnt lime, or glass production using renewable energies, the remaining CO_2 released by the chemical reaction e.g. from the calcination of limestone can be avoided via

- returning demolished concrete to the cement production process and thus closing the CO_2 loop (Heidelberg Cement 2021),
- increasing use of alternative construction materials, or
- avoidance of cement production via extending the use-phase of concrete-made structures (e.g. renovation instead of dismantling and new construction).

CO_2 from steel production is not a sustainable CO_2 source because an alternative route (direct reduction of iron with renewable hydrogen) can avoid CO_2 emissions from conventional steel plants based on blast furnace process. Similar arguments apply for CO_2 from fossil fuel combustion (use of renewable electricity including complementary energy storage).

3.4 Water demand

The water demand can be distinguished between green water, blue water, and grey water (Water Footprint Network 2021):

'Blue water footprint is water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time. Irrigated agriculture, industry and domestic water use can each have a blue water footprint.

Green water is water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. It is relevant for agricultural, horticultural, and forestry products.

Grey water footprint is the amount of fresh water required to assimilate pollutants to meet specific water quality standards. The grey water footprint considers point-source pollution discharged to a freshwater resource directly through a pipe or indirectly through runoff or leaching from the soil, impervious surfaces, or other diffuse source'

This concept is further illustrated in Figure 11.

Green water is not relevant for electricity-derived fuels, such as power-to-hydrogen or power-to-liquid. It has been assumed that closed water cycles and best available technology for water treatment is applied. Therefore, and for the lack of empirical data, no grey water footprint is assumed for power-to-hydrogen and power-to-liquid. As a result, only blue water is relevant for power-to-hydrogen and power-to-liquid.

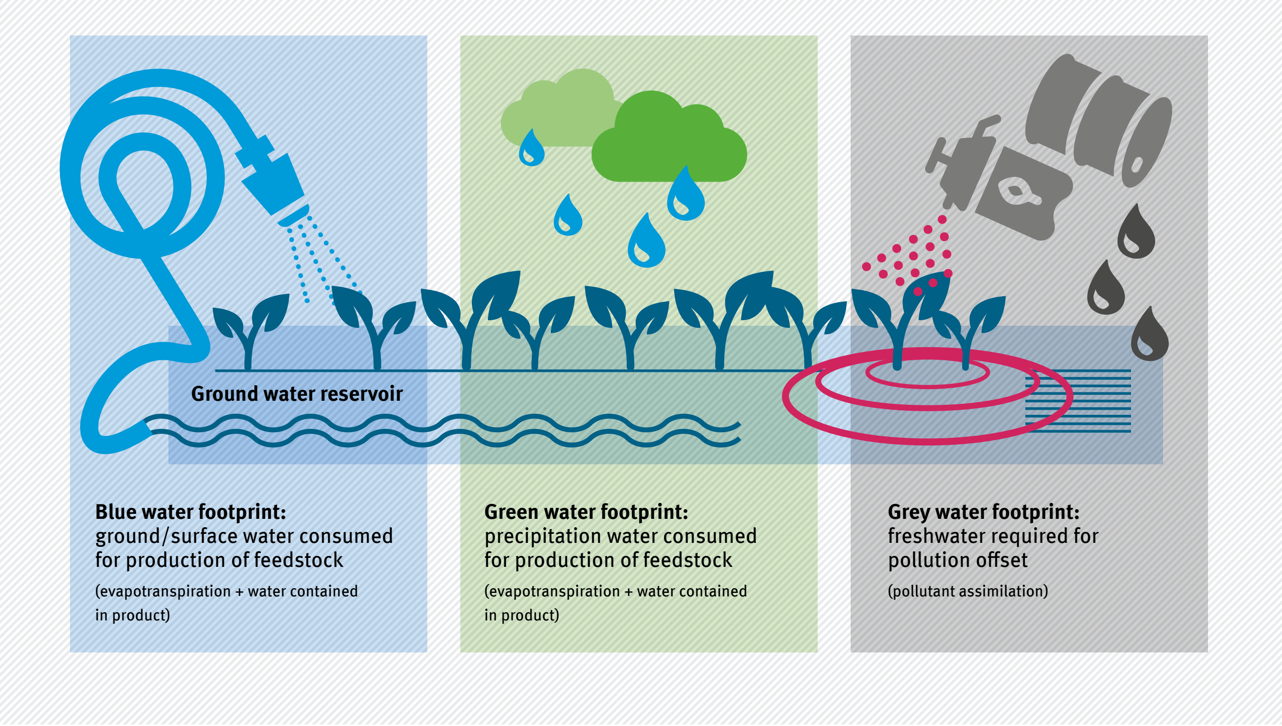
The net water demand depicted in Table 5 reflects the full water consumption for PtL fuel production. This includes the water demand as feedstock for water electrolysis, which is balanced against the water that is generated by synthesis reactions and other downstream processing steps according to the overall process stoichiometry.

However, besides the electrolysis reaction there are other water-consuming processes, e. g. for cooling and cleaning. The amount of water released by the synthesis processes is sufficient to meet the water demand as can be seen in the case of the Pearl GtL plant in Qatar (Shell 2021). As a result, it can be assumed that the water demand for the whole PtL plant is the water inserted into the electrolysis plant, i.e. follows as a function of the overall hydrogen demand.

For the methanol pathway the hydrogen demand amounts to about 1.24 MJ per MJ of final fuel (446 kg H_2 per metric t of final fuel) and for the Fischer--

Figure 11

Illustration of Blue, Green and Grey Water Footprint



Source: BHL, based on the water footprint concept presented in literature (Hoekstra 2003; Aldaya et al. 2012)

Tropsch pathway, the hydrogen demand amounts to about 1.40 MJ per MJ of final fuel (503 kg H_2 per metric t of final fuel). The water demand for water electrolysis amounts to about 0.074 kg per MJ of hydrogen (8.9 l per kg of H_2) leading to about 0.092 kg per MJ of final fuel (4.0 m³ per metric t of final fuel) for the methanol pathway and 0.105 kg per MJ of final fuel (4.5 m³ per metric t of final fuel) for the Fischer-Tropsch pathway.

Additionally, water is required for the cleaning of the PV plant. The water requirement for the cleaning of PV panels is indicated with about 0.022 kg per kWh of electricity for Germany and 0.040 kg per kWh of electricity for the MENA region (DLR et al. 2021). For wind power the water demand is negligible.

Besides the target output CO_2, the direct air capture (DAC) plant (based on vacuum temperature swing adsorption) also extracts some 1 kg of water per kg of CO_2 from the air (DLR et al. 2021). The amount of water extracted from air can thus meet some 80 % of the water demand of the water electrolysis process. However, the amount of water output from the DAC process depends on the ambient temperature and the humidity of the air.

As a result, depending on the electricity source 0.092 to 0.132 m³ of water per GJ of jet fuel or 3.2 to 4.5 liters of water per liter of jet fuel are required in the long term if the water extracted from air by the DAC is not included. Including the water extracted from air by DAC into the balance, 0.017 to 0.044 m³ of water per GJ of jet fuel or 0.6 to 1.5 liters of water per liter of jet fuel are required in the long term. On a side-note, this is in the same order of magnitude as e.g. (liquefied) hydrogen production from renewable sources with ~0.9 and ~0.8 m³/GJ in Germany and MENA, respectively, i.e. robustly low for PtX fuels in general.

A further advantage of PtL is a lower aquatic toxicity of the synthetic fuel product compared to conventional fuels. For instance, the company Shell indicates an aquatic toxicity classification that is lower for its synthetic diesel fuel compared to crude oil-based diesel (WGK 1 instead of WGK 2)[9]. This diesel fuel is produced via Fischer-Tropsch synthesis at Shell's GTL plant and is used e. g. as fuel for snow groomers

9 WGK: 'Wassergefährdungsklasse' (aquatic toxicity classification in Germany)

Table 5

PtL water demand (blue water) – long-term

(m^3/GJ)	Germany with DAC	Germany without DAC	MENA with DAC	MENA without DAC
PtL from utility-scale PV	0.030	0.103	0.044	0.132
PtL from onshore wind	0.019	0.092	0.017	0.105

MENA = Middle East / North Africa

Source: LBST

Table 6

Area-specific yield, area coverage and achievable air mileage related to the gross land area based on near-term and long-term PtL production efficiency

	Jet fuel* ($GJ\ ha^{-1}\ yr^{-1}$)	Area coverage	Achievable air mileage ($km\ ha^{-1}\ yr^{-1}$)
Near term (2020)			
PtL from utility-scale PV	820 – 2090	33 %	6990 – 17820
PtL from onshore wind	400 – 720	1.5 %**	3430 – 6130
PtL from PV/wind hybrid	1120 – 2570	32 %	9540 – 21890
Long term (2050)			
PtL from utility-scale PV	900 – 2340	33 %	7680 – 19930
PtL from onshore wind	440 – 810	1.5 %	3770 – 6860
PtL from PV/wind hybrid	1230 – 2870	32 %	10480 – 24480

* Bandwidth resulting from moderate vs. high-yielding power production locations and CO_2 sources available
** 5,500 m² for foundation, working space and access roads related to a gross land area of 360,000 m² per wind turbine (4 MW, 150 m rotor diameter, 4 rotor diameter distance between wind turbines)

Source: LBST

and other machines in the environmentally sensitive alpine region Zugspitze in Germany (Shell 2019).

3.5 Land use

Land requirement for PtL production is dominated by the land area for renewable electricity generation from solar or wind energy. The land area for CO_2 provision, water electrolysis and fuel conversion is significantly smaller. The area-specific yield of PtL is evaluated at the example of utility-scale PV and onshore wind power (see Annex 7.3 for assumptions). These exemplary cases are most relevant for the comparison with alternative jet fuel options in Section 4.1.2. Furthermore, concentrating solar power (CSP) or offshore wind energy provide important perspectives for PtL fuel production at scale. The area demand for DAC installations as e.g. indicated in Madhu (2021) is negligible compared to the gross area demand for renewable power plants.

Area-specific yields for PtL jet fuel production are given in Table 6 in form of achievable air mileage[10].

10 Air mileage = (1/aircraft fuel consumption)

The area coverage indicates the fraction of gross area demand land, which cannot be used for other purposes as it is covered by PV installations, wind tower foundation, or access roads. A specific air mileage of about 0.37 km per kg jet fuel is assumed (UBA 2016).

The evaluation of the gross area in Table 6 takes the land demand into account, which is needed to reduce shading of solar or wind energy installations to an economically reasonable level. The ratio between covered and gross land area is particularly large for wind parks, where more than 95 % of the area is still available for agricultural purpose or forestry. The coverage of solar power plants is much larger, however, electricity generation from solar (and wind) does not necessarily require arable land. In fact, the most suitable locations for solar energy generation are found in desert-like regions with high solar irradiation, which are unsuitable for agricultural use.

3.6 Fuel costs

Three different regions have been investigated for the estimation of the short and long-term costs of PtL-derived jet fuel:

- Central Europe (Germany as proxy)
- Southern Europe (Spain as proxy)
- MENA (Morocco as proxy)

Photovoltaic (PV) and wind power are to a large extent complementary in their production profile. In many cases, high PV electricity yields occur at periods with low wind speeds and vice versa. For the PtL plant a high equivalent full load period is beneficial. Therefore, the electricity for the PtL plants is supplied by PV/wind hybrid power plants. In case of Central Europe, the PtL plant is located nearby the PV/wind hybrid power plant. In case of Southern Europe and the MENA region where renewable water is scarce the electricity is assumed to be transported via a 200 km high-voltage direct current cable to the PtL plant at the coast where the water demand can be met by seawater desalination.

For PtL pathways the same cost assumptions have been applied as indicated in Soler & Schmidt (2021).

The investment of the PV plants has been derived from Cossu et al. (2021) and the investment for wind power from existing wind farms in the different regions. Single-axis solar tracking has been assumed for large-scale PV power plants in Central and Southern Europe and MENA.

Learning curves based[11] on (ISE 2018) and scenarios based on IRENA (2019a and 2019b) have been applied to take future cost reduction for PV and wind power into account. Starting from about 640 € per kWp the investment for large-scale PV plants with single-axis solar tracking decreases to about 360 € per kWp in the long-term (2050). Starting from some 1130 € per kW of rated power the investment for large-scale wind farms in MENA region decreases to about 960 € per kW of rated power. The costs for operation and maintenance for PV and onshore wind power plants amount to 18 € per kWp and year (Cossu et al. 2021) and 30 € per kW of rated power and year plus 0.005 €/kWh of electricity generated (ISE 2018), respectively.

At an interest rate of 4 % and a lifetime of 25 years, the long-term (2050) electricity supply costs from PV/wind hybrid renewable power systems amount to about 4.3 cents per kWh_e in Central Europe, 3.5 cents per kWh_e in Southern Europe, and 3.2 cents per kWh_e in the MENA region.

For the purpose of this study, the technical and economic data for the PtL plant have been scaled to a production capacity of 1000 kt of liquid hydrocarbons per year. The investment for water electrolysis is expected to decrease from about 1030 € per kW_e in 2020 to 390 € per kW_e in 2050 (Soler & Schmidt 2021). Vacuum temperature swing adsorption (TSA) has been assumed for the capture of CO_2 from air. CO_2 liquefaction and CO_2 buffer storage have been applied to provide pure CO_2 for the synthesis and to balance short-term fluctuations of the electricity supply.

The equivalent full load period of the PtL plant has been assumed equivalent to the capacity factor of the PV/wind hybrid electricity supply. It amounts to 3910 h/a year in Central Europe, 5040 h/a in South Europe, and 5600 h/a in the MENA region (Soler & Schmidt 2021). The electricity input of the electrolysis

11 The concept of “learning curve” depicts trends in price reduction for certain goods when production capacities expand. Generally, it is expressed in relative price decrease per doubling of production capacities. Thus, a learning curve trend of 30 % means that product prices (e.g. for electricity from solar PV) decrease by 30 % if production capacities double.

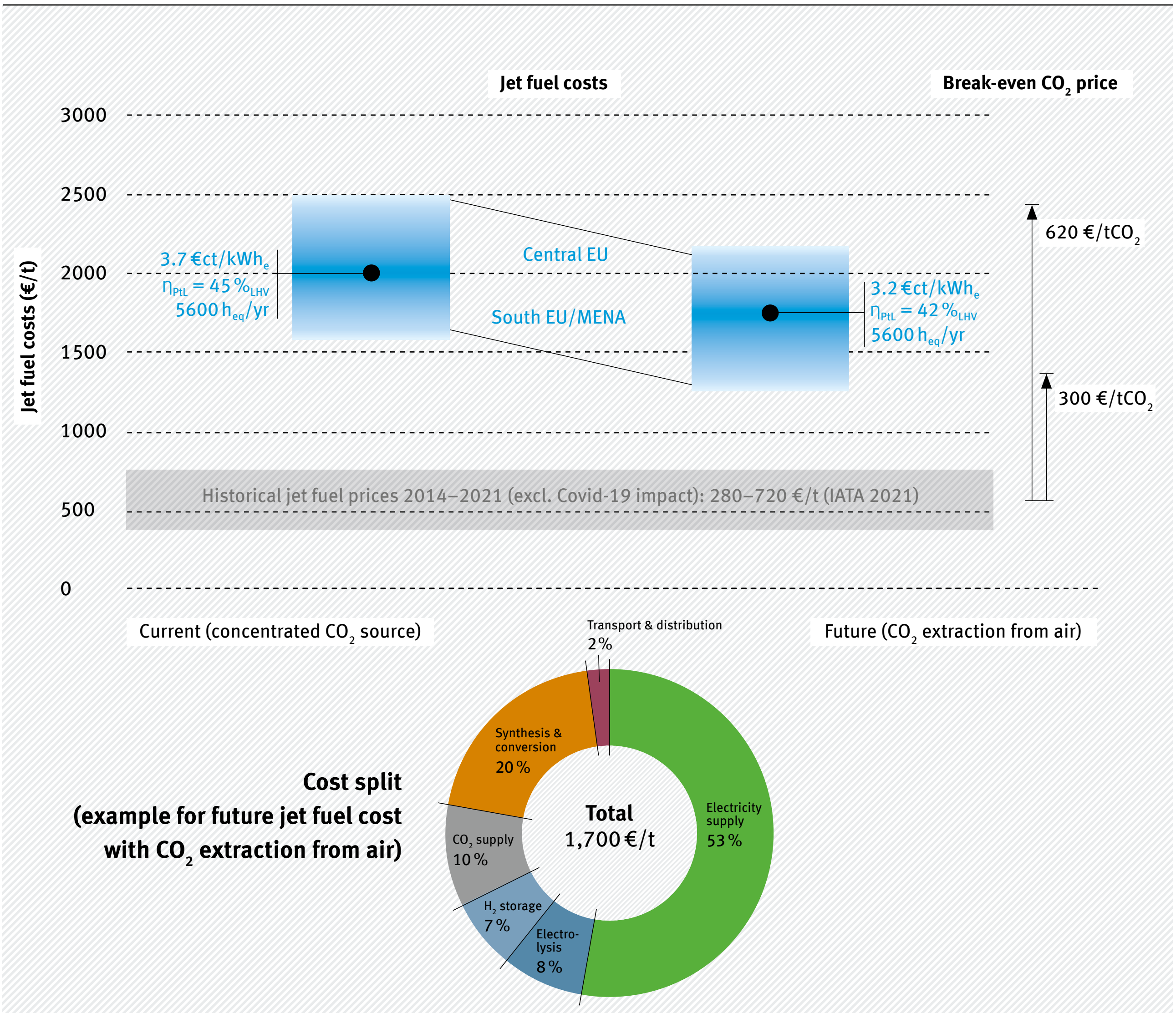
plant amounts to 2260 MW for the methanol pathway and 2560 MW for the Fischer-Tropsch pathway. The reason for the difference is the different hydrogen demand for these two pathways.

Table 12 and Table 13 in Section 7.2 show the near and long-term techno-economic data for the production of jet fuel via PtL conservatively assuming low-temperature electrolysis for all cases. Figure 12 shows the resulting near and long-term costs assuming CO_2 from a concentrated source and extracted from the air, respectively. The resulting production costs comprise three exemplary regions and two production pathways.

Figure 12 gives an overview of main cost constituents for the production and supply of PtL in the example of a PtL plant using CO_2 from a concentrated source today and direct air capture in the future in a Fischer-Tropsch process situated in MENA. The shares indicated in Figure 12 are in the same order of magnitude as for other PtL plant configurations. Electricity supply is the dominating cost element, followed by PtL process facilities comprising electrolysis, H_2 buffer storage, CO_2 extraction and storage (in the example: DAC). Due to the high energy density of PtL, transport and distribution of the fuel product has a marginal cost impact only. As the cost for PtL production is very much determined by investments into assets (PV,

Figure 12

Projection of jet fuel production costs for a range of current and future techno-economic assumptions



η = conversion efficiency

Source: LBST

wind, electrolyzer, synthesis, etc.) the discount rate assumption is among the most sensitive parameters in the economic assessment.

Jet fuel price ranged between 280 and 720 € per t during 2014 to 2021 (IATA 2021). According to IEA (2015) future jet fuel price could amount to 95 US$ per barrel in 2040, or around 837 € per t jet fuel. This price bandwidth serves as a fossil jet fuel price reference and has been assumed without a carbon price and without taxes. Hence, if jet fuel prices stay in the range that has been observed in the past few years, then a significant cost disparity between fossil jet fuel and renewable jet fuel can be expected to remain in the future. This cost gap is particularly the case for renewable options that offer both, potential scalability and high sustainability performance.

3.7 Air quality and high-altitude climate impact

The most direct pathways for PtL fuel synthesis via the Fischer-Tropsch and the methanol route yield a synthetic paraffinic kerosenes, which mainly contain n-alkanes and iso-alkanes, while the contents of cyclo-alkanes and aromatics are drastically lower compared to conventional jet fuel. One result of this difference in molecular composition is a significant reduction of soot formation from fuel combustion (Moore et al. 2017). Reduced soot formation is a direct air quality benefit, as less fine and ultrafine particles are formed. Furthermore, PtL fuels do not contain sulfur, while conventional jet fuel can contain up to 3000 ppm of sulfur according to current specifications[12]. Reduced sulfur oxide formation adds to the air quality benefits of synthetic kerosenes.

The reduction in particle emission further translates into a reduction of the high-altitude climate impact of aviation[13]. Particle emissions at cruise altitude act as nuclei for the condensation of water droplets, which ultimately form ice crystals. The net effect of aviation induced cloudiness, in form of persistent contrails and contrail induced cirrus clouds, is a temperature increase due to a change in the radiative balance (Kärcher 2018). Larger ice crystals are formed when a reduced number of condensation nuclei compete for the limited amount of available water vapor. The formation of larger ice crystals results in a shorter lifetime of aviation induced clouds (larger particles sink faster) and in a reduced optical density for the outgoing infrared radiation. The combination of both effects reduces the high-altitude climate impact (Burkhardt et al. 2018).

Further important contributions to local air quality and high-altitude climate impact relate to NO_x emissions (Grewe et al. 2017). Measurements in the exhaust stream of aircraft turbines indicate that the emission of NO_x was not significantly affected by synthetic fuel blending (Schripp et al. 2018). Synthetic fuels are therefore not the ultimate solution to address pollutant emission. The reduction of the full emission profile needs to be addressed by a combination of optimized combustion processes and clean burning fuels.

Aspects relating to differences in the chemical composition of synthetic kerosenes and crude oil-derived jet fuel were discussed from a fuel approval perspective in Section 2.2. The benefit of reduced particle formation from synthetic paraffinic kerosene combustion is directly linked to the low content of aromatics[14]. However, within the existing fleet of aircraft a certain level of aromatic content is required due to the interaction of the fuel with specific elastomers used for sealing (seal swelling). This technical issue is already addressed by major aircraft manufacturers, who announced that the fuel systems of few of their current and all future aircraft are specifically designed for using fuels with low aromatic content. The compatibility of future aircraft with synthetic paraffinic kerosene[15] is an important prerequisite to leverage the full benefit of clean burning fuels.

Another advantage of synthetic jet fuel is the lower toxicity due to lower content of aromatics and the absence of benzene.

12 The majority of sulfur contents found in two fuel quality studies from an US dominated and German context were in the 100 to 500 ppm range (Figure 5 in A. Zschocke, S. Scheuermann, J. Ortner 2017)
13 The high-altitude climate impact of aviation is of similar magnitude as the effect of cumulated CO_2 emissions from jet fuel combustion (see Section 1).
14 Due to their molecular structure aromatics are a dominant contributor to current particle emissions from conventional jet fuel combustion (Moore et al. 2015).
15 Synthetic paraffinic kerosene also violates other specifications of conventional jet fuel such as minimum density requirements. In the long run jet fuel specifications may be adapted towards the properties of synthetic paraffinic kerosene if synthetic fuels become dominant within the aviation sector.

4 Power-to-Liquids in comparison to other fuels

4.1 Sustainability aspects

The main motivation to replace crude oil derived jet fuels by renewable alternatives is the mitigation of climate change. Consequently, the global warming potential associated with the full life cycle is a key indicator to measure the environmental impact of fuel alternatives. Further highly relevant sustainability aspects are water demand and land use. In the following, these three criteria are used for a quantitative comparison of PtL fuels and the most common biofuel alternatives, namely Alcohol-to-jet (AtJ), Biomass-to-Liquid (BtL) and Hydroprocessed Esters and Fatty Acids (HEFA). Additional sustainability aspects are discussed qualitatively in Section 4.1.4.

The quantification of water demand, land use and global warming potential, is associated with significant uncertainty and variation. In case of PtL the main uncertainties, albeit at orders of magnitude lower scales compared to bioenergy pathways, relate to future technological assumptions such as energy efficiencies of electrolysers, conversion steps or CO_2 air capture systems. Even more pronounced than uncertainty effects are variations that depend on the particular context of a PtL plant: Solar and wind energy resources vary significantly across the globe; using hydropower or geothermal majorly affects many sustainability indicators. Moreover, the choice of the CO_2 source has a large impact, especially on the GHG emissions that are attributed to PtL fuel production. In the case of biomass-based fuels, the environmental performance varies to an even larger extent as it drastically depends on production processes or regional conditions like land-use changes, crop yields, water availability or ambient temperatures.

The following sections compare typical parameters for PtL production from solar or wind energy to representative performance parameters of biofuels from cultivated energy crops. The comparison illustrates that the area and water demand for PtL fuel production is much smaller compared to biofuels from energy crop cultivation. Furthermore, PtL provides the opportunity of even further reduced greenhouse gas emissions. This highlights the advantages of PtL fuels for renewable fuel production at the very large scale as it is needed to decarbonize aviation[16].

4.1.1 Water use

Water is a basic human need and a crucial commodity for agriculture, industry as well as the energy sector. As human activities demand and pollute water, local limitations of this resource become more and more apparent. According to the United Nations, billions of people live in water-stressed areas. Hence, clean water and sanitation is among their 17 Sustainable Development Goals (United Nations, 2015). Excessive use of water may lead to severe disruption of the local hydrological cycle and, concomitantly, sustainable water supply. Consequently, water consumption along the entire supply chain is an important consideration for the production of renewable fuels especially, when it comes to their large-scale implementation in arid regions.

In that context, the concept of a product's water footprint as a means of quantifying the direct and indirect water use associated with its production has been introduced nearly 20 years ago (Hoekstra 2003). As explained in Section 3.4, the concept differentiates between blue, green and grey water use (Aldaya et al. 2012): while blue and green water use both refer to the consumption of water e.g. because it is directly contained in a product or evaporates throughout the process, they differ in the type of water resource, i.e. surface and ground water for the former and rainwater for the later. This idea appears illustrated in Figure 11. Grey water use on the other hand is associated with a pollution offset, i.e. the amount of water that would be required to dilute water pollution below the relevant thresholds.

As mentioned above, quantification of the water footprint for a final product such as jet fuel, is not straightforward and absolute values depend on the assumptions taken throughout the assessment, such as location of the biomass and fuel production, irrigation requirements etc. To illustrate these

16 Biofuels from residue & waste can hardly be scaled towards future aviation fuel demand. In addition, the environmental burden of biofuels from residues or wastes is mainly attributed to the main product or activity (that generates the residue or waste), only the impacts that are associated with the final fuel conversion steps are attributed to the fuel product. This limits the direct comparability.

variations within pathways and differences across selected pathways, Annex Figure 16 shows global variations of water use for a number of feedstock applied in SAF production based on an assessment by (Mekonnen and Hoekstra 2010). The yellow points indicate the global average, which we will mainly focus on in the further analysis presented in this chapter.

Finally, these global averages of water use for feedstock production, i.e. bioethanol or biodiesel, are listed in Table 7 and used as a basis for determining the total water demand per liter of jet fuel produced. While the specific water demand of a biomass-based jet fuel depends on the feedstock used, the local climate and agricultural practices as discussed above, generally, biofuels have orders of magnitude higher water demand than their PtL-based counter parts.
The comparatively low water demand of the latter can be met by seawater desalination leading to an only slight increase of the electricity demand[17]. To put it in numbers comparing the water footprint of a liter of jet fuel produced from jatropha oil[18] via a HEFA-pathway with PtL fuel from renewable electricity, the average difference amounts to a factor >5000. This may be a pivotal consideration when it comes to widespread implementation of renewable fuels, especially when the expected global increase of fuel demand and water scarcity are taken into account.

Nonetheless, even with a comparatively minor water demand for the PtL route, local water availability is a relevant factor to consider in the environmental impact assessment that accompanies planning and locating production sites. This particularly applies for large-scale production facilities in water-stressed areas.

Table 7

Water footprint of various alternative fuel pathways (global average)

Feedstock (pathway)	Blue water (m^3 / GJ)	Green water (m^3 / GJ)	Grey water (m^3 / GJ)	Cumulative ($1000L_{H_2O}/L_{jet\ fuel}$)	Reference
Jatropha oil (HEFA)	335	239	n.a.	**21.8**	Feedstock to product conversion efficiencies: (Mäki-Arvela et al. 2021) (Geleynse et al. 2018)
Rapeseed oil (HEFA)	20	145	29	**7.68**	
Soybean oil (HEFA)	11	326	6	**14.48**	
Palm oil (HEFA)	0	150	6	**6.05**	Jatropha oil water demand: (Gerbens-Leenes et al. 2009)
Bioethanol from sugar cane (AtJ)	25	60	6	**3.91**	
Bioethanol from sugar beet (AtJ)	10	31	10	**2.20**	All other feedstock water demand: (Mekonnen & Hoekstra 2010)
Bioethanol from maize (AtJ)	8	94	19	**5.21**	
PtL via FT	0.12	n.a.	n.a.	**0.0041**	LBST, this study
PtL via methanol	0.11	n.a.	n.a.	**0.0037**	LBST, this study

Pathway-specific feedstock to product conversion efficiencies and product fraction distributions have been taken from the references specified and considered in the calculations. Water footprints have been allocated to the respective products according to their energy content as proposed by Prussi et al. (2021).

17 ~3 kWh per m^3 of water or about 0.0013 GJ per GJ of final fuel, i.e. the energy demand of desalination is almost negligible, notably it is much lower than the energy demand for electrolysis or CO_2 air capture.
18 While Jatropha plants are known to be tolerant to marginal water supplies, marginal inputs also result in marginal yields.

Figure 13

Water demand of different jet fuel production pathways in comparison

(Volume representation, PtL water demand 4 $L_{H_2O}/kg_{jet\ fuel}$)

Source: BHL/LBST

4.1.2 Land use

Table 8 lists area-specific yields and achievable air mileages of PtL jet fuels produced from PV and wind power in comparison to several biomass-based production pathways. Correspondingly, Figure 14 displays the area which needs to be cultivated for one year in order to produce one ton of jet fuel for the different fuel production pathways. It is evident that the areas needed for jet fuel production via PtL routes are much smaller compared to the area demand of fuels from cultivated biomass.

Displayed is the gross area demand for all pathways, i.e. the total area required. The net land area demand, on the other hand, refers only to the area actually occupied that cannot be used elsewise. While for biomass-derived fuels both figures are equal, for PV plants or, even more so, wind parks the net area demand is significantly smaller. Dual-use – especially in combination with agricultural applications – presents an opportunity for increasing the efficiency of utilization of land as a limited resource.

Another key aspect that should be considered is the type of land, which is used. As renewable power can be produced on virtually any kind of land area and even water bodies[19], i.e. is largely independent from arable land, the risk of competition between energy and food is virtually eliminated.

19 e.g. offshore wind parks (incl. fixed and floating foundations) and recently also floating PV systems

Table 8

Area specific jet fuel yields and achievable air mileage for different biomass based as well as PtL based fuel production pathways

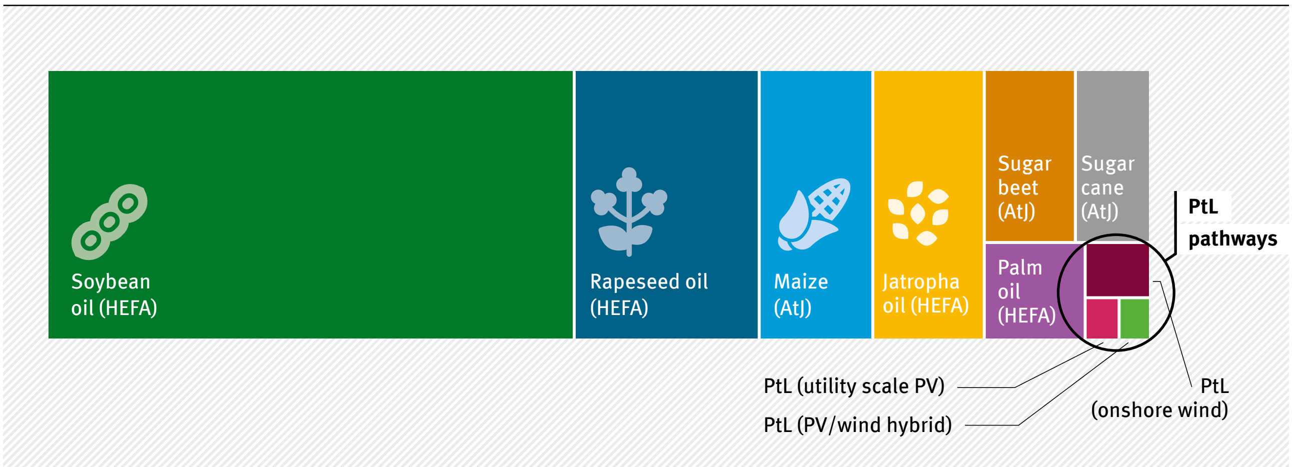
Feedstock (pathway)	Area specific jet fuel yield (GJ ha^{-1} yr^{-1})	Achievable air mileage (1000 km ha^{-1} yr^{-1})
Jatropha oil (HEFA)	57 (1,2)	0.49
Rapeseed oil (HEFA)	35 (1,2)	0.30
Soybean oil (HEFA)	12 (1,2)	0.10
Palm oil (HEFA)	176 (1,2)	1.50
Bioethanol from sugar cane (AtJ)	135 (3,4,5)	1.15
Bioethanol from sugar beet (AtJ)	110 (3,4,5)	0.938
Bioethanol from maize (AtJ)	57 (3,4,5)	0.49
PtL (wind)	442 – 805	3.77 – 6.86
PtL (PV)	901 – 2339	7.88 – 19.93
PtL (PV/wind hybrid)	1230 – 2873	10.48 – 24.47

Pathway-specific feedstock to product conversion efficiencies and product fraction distributions have been taken from the references specified and considered in the calculations. Areas have been allocated to the respective products according to their energy content as proposed by (Prussi et al. 2021).

(1) Oil yield [kg oil/ha/yr] for Jatropha oil (1590), Rapeseed oil (1000), Soybean oil (375) and palm oil (5000) (Zulqarnain et al. 2021)
(2) Fuel yield [kg fuel / kg oil] Jatropha oil (0.83), Soybean oil (0.75), Palm oil (0.0.82) and Rapeseed oil (0.80, mean value of other three) (Mäki-Arvela et al. 2021)
(3) Global biomass yields [t/ha/yr] for maize (7.23) and sugar cane (75.74) (FAOSTAT 2021)
European biomass yield [t/ha/yr] for sugar beet (55.93) (FAOSTAT 2021)
(4) Conversion efficiency [kg feed / kg EtOH] for maize (3.2), sugar beet (12.7) and sugar cane (14.1) (Eckert et al. 2018)
(5) Jet fuel efficiency [kg EtOH / kg jet fuel] for all AtJ pathways (1.725)

Figure 14

Gross area needed for cultivation in order to yield one ton of jet fuel per year



Source: BHL

4.1.3 Global warming potential

As illustrated in Section 1, aviation (and the transportation sector in general) aims at a substantial reduction of its climate impact. Consequently, the prospect for a high GHG emission reduction potential attracted attention to alternative jet fuel production pathways. In fact, most definitions of SAFs employ the metric of GHG emissions expressed in carbon dioxide equivalents (CO_2eq) as the defining factor (ICAO 2019; Jeswani et al. 2020). This parameter is quantitatively assessed through all stages of life; the corresponding methodology is termed life cycle analysis (DIN EN ISO 14044:2018-05, DIN EN ISO 14040:2021-02). As opposed to fossil fuels, renewable fuels can partly offset the emissions caused by their production and their combustion for aircraft propulsion by absorbing atmospheric CO_2 as carbon source either for biomass growth or as direct process feed as in the PtL pathway.

As illustrated in Table 9, the latter is capable to outperform HEFA and AtJ production pathways when it comes to direct GHG emissions. In order to tap the full potential of GHG emission savings, however, the choice of CO_2 source and type of electricity is of crucial importance (see Section 3.3). The strong dependency on the origin of the feedstock CO_2 roots in the fact that removal of atmospheric CO_2 and its utilization in PtL fuel production offsets in-flight emissions resulting in net-emission reduction when compared to fossil kerosene. At the same time, the source of electricity is a major consideration in overall GHG emissions of PtL fuels with renewable electricity being the key to a low-emission PtL fuel.

While the assessment of direct GHG emissions is quite well established, quantifying the influence of repurposing land for biomass production at the expense of natural ecosystems or agricultural use for food production on that metric is not as straightforward. The so-called direct and indirect land use change (LUC)[20] is heavily situational and, consequently, bears a strong variability (IIASA 2013; Jeswani et al. 2020). This is especially true for indirect LUC (see Table 9), which is considered a highly relevant research matter when it comes to biofuel sustainability.

20 Direct land use change (dLUC) is defined as the direct transformation of any type of land (e.g. forest, grassland; cultivated or uncultivated) into cropland used for biofuel feedstock production. Greenhouse gas emissions from dLUC can be attributed to individual projects.
Indirect land use change (iLUC) describes the displacement of food and feed crop production to previously uncultivated land areas caused by the additional land demand for biofuel feedstock production. (Jeswani, 2020) The concept of iLUC describes changes in land-use patterns of whole regions and can thus typically not be attributed to individual projects.

Table 9

“Well-to-Wake” greenhouse gas emissions of various production pathways towards jet fuel with and without accounting for emissions through land use change

Feedstock (pathway)	GHG emissions without LUC ($g_{CO_2eq}/MJ_{jet\ fuel}$)	GHG emissions incl. LUC ($g_{CO_2eq}/MJ_{jet\ fuel}$)	Reference
Jatropha oil (HEFA)	40.0	13 – 141[1]	(Kolosz et al. 2020)
Rapeseed oil (HEFA)	46.6	69.6[2]	(Zhao et al. 2021; Prussi et al. 2021; ICAO 2021a)
Soybean oil (HEFA)	39.7	61.8[2]	(Zhao et al. 2021; Prussi et al. 2021; ICAO 2021a)
Palm oil, open pond (HEFA)	57.8	96.8[2]	(Zhao et al. 2021; Prussi et al. 2021; ICAO 2021a)
Palm oil, closed pond (HEFA)	37.4	76.5[2]	(Prussi et al. 2021; ICAO 2021a)
Palm oil (HEFA)	51.9 – 94.5	57.1 – 126.7[1]	(O’Connell et al. 2019)
Bioethanol from sugar cane (AtJ)	24.1	33.1[2]	(Prussi et al. 2021)
Bioethanol from sugar beet (AtJ)	50.9		(Moretti et al. 2021)
Bioethanol from maize (AtJ)	65.7	90.7[2]	(Prussi et al. 2021)
Miscanthus (BtL)	10.4	-11.6[1]	(ICAO 2021a)
Poplar (BtL)	9.0		(Jong et al. 2017)
PtG LH_2	4 – 9	n. a.	LBST, this study
PtL	5 – 10	n. a.	LBST, this study
Crude oil	89.0		(ICAO 2021b)
Natural gas (GtL)	91.0		(Wong 2008)

1 indirect LUC
2 direct LUC
n. a = not applicable

The full climate impact of aviation is not only caused by GHG emission, but also by high-altitude effects which are specific to the aviation sector (see Sections 1 and 3.7). Most synthetic kerosenes reduce soot emissions compared to conventional jet fuel, which in turn reduces climate effects of contrails and induced cirrus clouds. The aromatic content of all investigated fuel options is low, therefore the performance of HEFA, AtJ, and FT-SPK with respect to high-altitude climate impact are expected to be similar.

4.1.4 Further sustainability aspects

Out of many indicators, three indicators with specific importance were chosen as main criteria for this report, namely water use, land use and greenhouse gas emissions. The comparison of power-to-liquid fuels to other fuel alternatives can, however, be extended to further aspects of sustainability.

The production of renewable fuels, both in case of biofuels and PtL fuels, is associated with larger efforts than conventional fuel production, e.g. in terms of **energy and material demand.** A recent study found that the acidification and eutrophication potential of synthetic fuel production compared to conventional fuels might be between 2 and 3.8 times as large, respectively; in case of PtL from renewable sources the acidification may range between a factor of 1 and 2.8 (A. Liebich et al. 2020). It is important to note that the material demand, though significantly higher, for a transition to renewable energy carriers is within planetary boundaries. For instance, analyses of electricity generation via PV at very large scale revealed that resource demand is tolerable, but flat glass production capacities need to be significantly increased to serve global energy needs by solar PV (Jean et al. 2015). This illustrates the dimension and the challenges that go hand in hand with the transition to renewable energy carriers. Consequently it will remain important to improve energy efficiencies where possible and to be aware of the energy demand side, not only for cost reasons, but also due to the environmental impact of large-scale renewable fuel production.

Another important consideration, especially in the context of biomass-derived fuels, is **biodiversity.** Feedstock cultivation may drastically affect local ecosystems by restricting the extent of natural habitats and creating imbalances from the extensive cultivation of a specific species. 'Advanced biofuels' as defined in the EU RED II are expected to offer a better environmental performance compared to processing conventional (1st generation) energy crops. Especially if processing biogenic residues and waste streams, this can significantly reduce the burden on biodiversity (Jeswani et al. 2020) provided that waste and residue streams adhere to the waste hierarchy and are thus part of a wider circular economy approach. Using residues from unsustainable practices on the other hand, such as input-intensive agricultural mono cultures or intensive livestock farming, bears "lock-in" risks of pertaining unsustainable practices.

Renewable fuel production may also diversely influence the **socio-economic development** of a region (Hunsberger et al. 2017). While production facilities create opportunities for the development of infrastructure and job security, there can also be significant hurdles to reach these aims, which can be largely interrelated to inclusion and acceptance of local population.

4.2 Economic competitiveness

Power-to-Liquid fuels are not yet produced at scale. Nevertheless, their economic performance has been improving over the past years. This is mainly due to cost reductions of key subsystems, such as renewable electricity generation or electrolysers. Furthermore, an increasing number of research and development projects address technological challenges regarding e.g. fuel conversion and CO_2 provision via direct air capture. Nevertheless, the projected production costs of PtL fuels remain substantially higher than fossil jet fuel at current market conditions. In September 2021 jet fuel prices amounted to 600 €/t[21] (~50 €ct/L), while much higher PtL production costs are projected even in case of optimistic assumptions (well above 1000 €/t, see Figure 12). Likewise, the production costs of aviation biofuels are substantially higher than crude oil-derived kerosene prices. Consequently, it is necessary to bridge a significant price gap in order to introduce any renewable jet fuel into the market.

Most policies that support the early market introduction of SAF involve blending mandates or similar regulatory measures[22]. In some cases, sub-quota for PtL fuels are planned to specifically support the early scale-up of synthetic fuel production from renewable electricity (European Commission 2021). Specific support mechanisms for PtL fuels or biofuels from advanced feedstock are introduced as the market for renewable jet fuel is currently dominated by HEFA fuels (Hydrotreated Esters and Fatty Acids), which are produced from plant oils or animal fats. The technologies for jet fuel production from plant oils and fats are mature. Until recently, HEFA fuels were also the most cost-effective biofuel option for aviation driven by low capital cost of HEFA fuel production and a dominating role of the feedstock cost. Spot market prices for plant oils steeply increased during 2021. Current price levels are more than a factor of two higher compared to 2019[23], which brings HEFA production cost at current market conditions within the range that is

21 Between 2015 and 2019 jet fuel prices fluctuated between 35 $/bbl and 95 $/bbl, pre-Covid price levels around 80 $/bbl were reached again by mid-2021: www.iata.org/en/publications/economics/fuel-monitor/

22 In principle it is possible to bridge the existing price gap by CO_2 emission costs. The necessary carbon pricing to induce SAF demand is substantial, as a rule of thumb: 100 €/t_{CO_2} correspond to about 25 ct/$L_{jet\ fuel}$

23 Wholesale prices as of 29.9.2021: Rapeseed oil: 1385 €/t, Palm oil: 1090 €/t, UFOP-Market-Information "October 2021" www.ufop.de/index.php/download_file/10582/781/

anticipated for future PtL production. It is unclear if such market prices will persist, but it is clear that the main bottleneck of the HEFA pathway is the limited availability of sustainable feedstock. For example, approximately half of the used cooking oil currently used in the EU as feedstock for biofuel production (such as HEFA) is already imported from countries as far as China (CE Delft 2020). The relevant competition for the bulk part of the required volumes of renewable fuels is thus between PtL and biofuels from more abundant lignocellulosic feedstock. Similar to PtL, the ramp-up of biofuel production capacities from lignocellulosic feedstock is still in its infancies. Some recent cost projections of BtL production from agricultural residues or cultivated energy crops fall within the cost range that is expected for future PtL production (Pavlenko et al. 2019). Similar cost levels are expected for AtJ production from cellulosic ethanol (Pavlenko et al. 2019). However, other researchers expect that BtL fuels can be produced at significantly lower cost than PtL (Isaacs et al. 2021). Apart from cost projections, which are usually based on assumptions of capital and operational cost for future plants, conversion technologies need to reach commercial maturity, value chains need to be established and sufficient amounts of feedstock need to be aggregated at each plant location. Specific challenges need to be addressed for PtL as well as for various advanced biofuel pathways in order to achieve the first percentages of market penetration.
In many cases regional aspects will play an important role for the competitiveness of the individual options, such as feedstock availability, solar and wind energy resources, but also country-specific differences in supporting schemes.

In the long run it will be important that PtL fuels become price competitive at least in comparison to biofuel production from advanced feedstock. Figure 12 identifies the renewable electricity as the dominant cost item in PtL production. Prices for renewable electricity generation from solar and wind energy substantially declined since many countries around the world started introducing dedicated support mechanisms in the late 1990s/early 2000s. According to the International Renewable Energy Agency (IRENA), the last 10 years represented a “remarkable period of cost reduction for solar and wind technologies”, with onshore wind cost dropping by 56 % and solar PV cost even by 85 % (IRENA 2021). Considering current electricity prices of 3-5 ct/kWh (see Section 3) and recent learning curves, it can be expected that renewable electricity cost will consistently become lower than electricity from fossil sources, and that capacities for renewable electricity generation will continue to expand rapidly. Likewise, it may be expected that a continued market uptake of hydrogen technologies in other sectors of the economy gradually reduce the cost of electrolysers via technology development and economies of scale. Potential synergies with other sectors are much less pronounced for all energy conversion steps from renewable hydrogen to finished jet fuel. All major process steps already achieved a high level of technological readiness (see Table 2) but their integration into optimized PtL plants and the ramp-up of production capacities including all value chains is necessary to produce large volumes of synthetic fuels at a competitive price tag.

A major uncertainty regarding upscaling of production capacities comes from the development of carbon capture technologies, most notably, direct air capture (DAC). To date, only small demonstration plants for direct air capture exist, and levelized cost per ton CO_2 captured make up a noticeable share of total PtL cost (see Figure 12). Considering the tremendous amounts of CO_2 needed for the future demand of PtL jet fuels, cost reduction and capacity expansion of DAC will become one of the major economic challenges for a broad supply with PtL fuels.

Finally, economic competitiveness is tightly connected to investment certainty. With major regulatory initiatives on the way to implement binding PtL blending quotas in various countries and at the EU level, future investments in PtL production facilities are gaining planning certainty.

4.3 Complementary long-term options

Large-scale hydrogen production from renewable electricity via electrolysis has the potential to meet the future energy demand of various sectors. In aviation, power-to-liquid offers a credible pathway for jet fuel production from renewable hydrogen and CO_2 by utilizing technologies that have already achieved a high level of technological maturity (see Section 3.1). Complementary options for long-term aviation fuel production include (i) hybrid production pathways, which combine hydrogen from renewable electricity with biomass conversion in regions with abundant bio-feedstock, (ii) fuels from direct conversion of sunlight in regions with high shares of direct solar irradiation, and the perspective to utilize (iii) liquefied hydrogen directly as a fuel for future transport aircraft.

All bio-kerosene pathways consume hydrogen, at least during the final upgrading and refining steps. Large shares of renewable hydrogen can be utilized where hydrogen is needed for the main step of biomass conversion. This is e.g. the case for so-called **PBtL pathways,** where the synthesis gas from biomass gasification is combined with renewable hydrogen for Fischer-Tropsch conversion (Dietrich et al. 2018). Biomass gasification yields a synthesis gas with a H_2-to-CO-ratio that is not sufficient for Fischer-Tropsch conversion. In order to generate additional H_2, typically a water-gas-shift reaction is employed yielding H_2 and CO_2 from CO and H_2O. Supplying the required amount of H_2 by electrolysis instead improves the carbon efficiency of the biomass conversion. Such schemes are in particular appealing for waste-based fuel production and for regions that have large quantities of lignocellulosic residues in place.

The direct conversion of sunlight via **photo-electrochemical cells or solar-thermochemical pathways** omits the need for intermediate electricity generation. The most advanced solar-thermochemical fuel pathway is based on two-step redox cycles to directly produce H_2 and CO from H_2O and CO_2 using concentrated solar radiation (Koepf et al. 2019). Direct syngas production and subsequent synthesis of Fischer-Tropsch fuels has been demonstrated in the field within the EU project SUN-to-LIQUID (TRL 5) (SUN-to-LIQUID project). It may also be fruitful to combine carbon monoxide from direct solar conversion with electrolysis hydrogen in future solar refineries. Solar concentrating technologies can also provide heat to several process steps along synthetic fuel production pathways, e.g. for direct CO_2 air capture, high-temperature electrolysis, or thermochemical processes such as tail gas reforming or reversed water-gas shift.

Recently, the perspective to use **hydrogen directly as a fuel** for future transport aircraft received significant attention. The main advantages lie in a higher efficiency of hydrogen production compared to PtL, avoiding a dependence on a carbon source, and a drastically reduced emission pattern from final fuel combustion[24]. It is generally accepted that liquefied hydrogen at cryogenic temperatures (boiling point: -253 °C) is needed to meet the specific energy density requirements of large transport aircraft. This implies a substantial redesign of state-of-the-art aircraft concepts and involves major technical challenges especially regarding the tank design and fuel distribution on board of the aircraft. In case these technological challenges involved with hydrogen aircraft can be overcome, the market entry of large hydrogen aircraft is expected to take place at least 15 years from now; the penetration into the fleets will take even more time[25]. Hence, it is to be expected that drop-in renewable fuels will remain the corner-stone of climate change mitigation strategies in the foreseeable future.

5 Conclusions and future perspectives

5.1 PtL – a scalable and sustainable fuel supply perspective for aviation

During the past years, PtL fuels from solar and wind power were increasingly recognized as a scalable and sustainable fuel supply option for aviation, but PtL fuels are not yet produced at relevant scale. However, numerous research-scale demonstration projects, a first demonstration flight as well as a first commercial PtL fuel production plant indicate that a formative phase of PtL up-scaling and market deployment has begun. Nevertheless, the challenges associated with a rapid industrialization of PtL fuel production towards a significant share of future jet fuel demand are substantial. Production costs of PtL fuels are still much

24 Most aircraft concepts foresee hydrogen combustion in gas turbines. Hydrogen combustion will not produce soot or CO, furthermore it provides the potential to significantly reduce NO_x emissions. For small to medium-size aircraft also hydrogen fuel cell-electric propulsion systems have been proposed. Pure battery-electric propulsion may be an option for small and short-distance aircraft only.

25 Current developments focus on small to medium-sized hydrogen aircraft. The advent of meaningful long-range aircraft is associated with higher technological risk and may require an even longer time.

higher than current jet fuel prices, while aggressive market-entry scenarios would be needed for a timely mitigation of climate change. In the following, we provide a more detailed summary of strengths, opportunities, challenges and potential concerns associated with PtL fuels.

Strengths

Producing aviation fuel via the PtL pathway allows tapping into the enormous global potential of renewable electricity, harvesting the energy provided by sun and wind, among others. In combination with a sustainable and scalable carbon source, such as CO_2 extraction from air, the overall process yields a sustainable jet fuel solution that can meet future aviation fuel demand. PtL fuels' well-to-wake GHG emissions can be near zero, while substantially less water and land is required for their production than for biofuels. Comparing to crude oil-based jet fuel, toxicity is reduced as well. At the moment, PtL fuels can be blended with conventional jet fuel up to a ratio of 50 %. The resulting fuel blend is "drop-in" capable, which ensures compatibility with the existing aircraft fleet and enables immediate emission reduction of aviation without needing to overcome technological challenges on the aircraft-side first.

Opportunities

The use of synthetic fuels brings along the potential of emission reduction through cleaner fuel combustion. More specifically, as aromatics and sulfur contents in synthetic fuel are very low to zero, particulate matter emissions are reduced and SO_x emission are avoided. Local air quality can substantially improve, benefitting not only the environment but also the health of the local population. Furthermore, the high-altitude climate impact is reduced due to different properties of aviation induced clouds in case of lower particle emission.

Additionally, PtL production sites require renewable electricity, thus supporting infrastructure development and strengthening local economies in regions with substantial wind and solar power potentials. As the latter often coincides with challenges for profitable cultivation, PtL production provides opportunities to communities in dryer/arid regions as there is no need for arable land. Another important benefit of PtL production is the provision of grid ancillary services, e.g. compensating for an imbalance of supply and demand of electricity. Lastly, the substantial amount of green hydrogen needed in the production process can provide momentum for establishing hydrogen value chains.

Challenges/weaknesses

The PtL pathway is comprised of several process steps. Each process step is associated with an energy requirement, a limited conversion efficiency and cost. Combined with significant levels of fuel demand, today and projected, this results in a substantial overall energy demand which needs to be satisfied by huge amounts of renewable electricity. Production efficiency is associated with cost contributions that pile up to high overall fuel production cost. Next to electricity cost, also electrolysis, synthesis and conversion plants and the provision of CO_2 are relevant cost contributors. Learning curves suggest a cost reduction for all the above-mentioned cost items, nevertheless production costs are expected to remain substantially higher than current fossil fuel prices.

In addition, the extent of the PtL related CO_2 and renewable electricity demands represent a major challenge. Meeting climate targets by substituting conventional jet fuel would require a rapid scale-up to bring supplies to an adequate level. Solar and wind energy are already deployed at rates of 100 GW per year. Nevertheless, the required roll out of additional renewable generation capacity can be challenging, both in densely populated regions (where suitable areas may be scarce) and at remote locations (due to a lack of infrastructure / skilled workers). In case of CO_2 air capture, current production capacities are at the stage of a few demonstration systems. Large-scale deployment of PtL will therefore require a steep ramp-up of production capacities for CO_2 extraction from air.

Finally, it should be noted that, while net CO_2 emissions can approach zero, particulate matter and NO_x emissions from combustion are not completely eliminated by the PtL approach.

Potential concerns/threats

A potential concern is that an increased availability of PtL fuels usable in conventional aircrafts' propulsion systems relaxes the pressure to innovate with new aircraft concepts using non-carbon based fuel options or involving other substantial technological modifications.

Another concern relates to the utilization of point source CO_2 from industrial facilities, which may create 'lock-in' effects with established technologies or in sectors that would otherwise decarbonize. The same is true for utilizing primarily non-renewable electricity. Not only would these measures prevent harvesting the potential environmental benefit, it would also cause a lock-in of conventional fuels, thereby defeating the intrinsic aim.

As with many large-scale infrastructure projects, the acceptance of the local population, e.g. for massive deployment of renewable power generation plants altering the landscape, represents a potential concern not only in the PtL context. It should be noted, though, that the land use of PtL fuels – while substantial in absolute terms in case the expected aviation fuel demand is fully met by PtL – is modest compared to biomass-based fuel options.

5.2 Pathway from first commercial projects to fuel production at scale

Early phase of scale-up

The early phase of scale-up where the first percentages of market penetration need to be established, is often perceived as the most difficult phase. Considering the high upfront cost for PtL production facilities, triggering market formation requires the generation of a stable demand. This can be achieved via an improvement of awareness by flight passengers demanding for an SAF compensation, fuel offtake agreements in line with sustainability strategies of airlines, or by public support in terms of subsidies or regulatory obligations to feed-in PtL.

The early phase of PtL fuel production is taking shape. Many relevant actors acknowledge the necessity for a defossilization of aviation and agree that PtL fuels can play an important role. In turn, policy support for the uptake of PtL fuels, especially at the EU level, is becoming more and more specific, so that investment certainty increases. As a consequence, further commercial PtL plants will become operational during the upcoming years. Substantial production capacities can be expected for the time horizon 2025 onwards.

It is likely that early PtL projects will often rely on renewable electricity supply from existing generation capacity and on CO_2 point sources, preferably of renewable origin. Therefore, it is important to design appropriate frameworks that ensure the sustainability of PtL fuel production on one hand, but do not delay the implementation of early demonstration projects on the other hand. For the preparation of large-scale deployment, further key technological challenges need to be addressed, such as the operational flexibility of fuel synthesis processes to work well with intermittent solar and wind energy profiles, or the development and integration of CO_2 air capture systems.

Large-scale deployment of PtL production capacities

After the early phase of industrialization, new challenges have to be overcome for a large-scale deployment. In particular, a sustainable supply of water, CO_2, and additional renewable electricity needs to be guaranteed. This requires robust sustainability safeguards at international level and a traceable monitoring system. A particular challenge lies in the provision of sufficient CO_2 from the air, as the availability of sustainable CO_2 point sources is limited.

Due to the scale of the required transition[26], socio-economic impacts will become increasingly important, especially in case of large-scale PtL deployment in economically challenged regions, but also in terms of acceptance of extensive renewable electricity generation capacity. Therefore, it will be important to involve all relevant stakeholders in sufficient time and to ensure that the local population can benefit from PtL deployment and production.

The large-scale deployment of PtL production capacities will also require adequate political measures that favor fuels with large sustainability benefits in terms of greenhouse gas emission reduction potential, land requirement and water demand. Further, the prices for fossil and PtL fuels need to converge in the long run, which should be achieved by both cost reductions of PtL production, and reasonable pricing of fossil fuels by internalizing their environmental cost or via quota obligations as proposed in the current ReFuelEU Aviation initiative (European Commission 2021).

26 In 2019 the worldwide airline industry spent 186 billion dollars for jet fuel (www.iata.org/en/publications/economics). This value will even increase in the future assuming higher fuel consumption and higher cost for renewable jet fuel. Non-action will, however, result in even higher costs (Stern 2007) and associated socio-economic impacts.

Logistics and siting

The most suitable locations for cost-efficient PtL production are in regions with high renewable energy potentials, such as windy regions or deserts with high solar irradiation. Consequently, it may be expected that the bulk part of PtL fuel production will concentrate in areas with excellent renewable energy potentials. To some extent, PtL intermediates, such as power-to-methanol or Fischer-Tropsch syncrude, can be transported to central upgrading and conversion facilities to benefit from economies of scale. In case of the utilization of CO_2 point sources, PtL deployment is bound to the source of CO_2. Limitations apply both to the total amount of fuel that can be produced in a region using acceptable CO_2 sources and to the capacity of individual PtL plants that are ideally sited in close proximity to the CO_2 source to avoid its transportation.

Due to favourable storage and logistics properties and existing infrastructures PtL offers a long-term perspective for many oil exporting countries and further territories with significant solar and wind power potentials in excess of their own needs.

Towards an approval of fully synthetic jet fuel

Few years ago, FT-SPK, which can be used in blends of up to 50 % with conventional jet fuel, was the only viable option to introduce PtL fuels into civil aviation. FT-SPK has a higher specific energy density and combusts cleaner than conventional jet fuel. Meanwhile, FT-SPK/A as well as co-processing of crude FT product in conventional refineries is approved[27]. In the long-run, an approval of full synthetic jet fuel is needed. The approval of FT-SPK/A[28] prepares the ground for fully synthetic jet fuels which are blended from several product streams in order to mimic all relevant properties of conventional jet fuel. Such a fully synthetic jet fuel enables a pathway to net carbon neutrality for the existing fleet of aircraft.

However, the intentional production of (soot-forming) aromatics is at odds with efforts to reduce air quality emissions and high-altitude climate impact of aviation. Flight tests already demonstrate the compatibility of the most recent transport aircraft with neat synthetic paraffinic kerosene. The vision is to make all new transport aircraft compatible with low-aromaticity synthetic kerosene to leverage the full potential of synthetic fuels, which inevitably requires a new set of standard specifications for aviation turbine fuels that are no longer produced from crude oil. It is clear that aromatics-free fuels are not compatible with many existing aircraft, therefore a separate fuel infrastructure will be required during the transition phase.

Methanol-derived kerosene is not yet approved for civil aviation. The expected molecular composition indicates that technical compatibility is likely. Nevertheless, fuel approval processes in aviation may take several years and commercial production of PtL via the methanol route is only possible upon approval. Therefore, it is vital for the methanol pathway to engage in the approval process as early as possible.

27 The co-processing option is important for two main reasons. Smaller FT facilities can omit product upgrading and instead provide an intermediate synthetic crude to centralized refineries. Furthermore, refineries that co-process FT syncrude mainly to fulfill quota for diesel fuel, have the opportunity to sell the kerosene product into the jet fuel market.
28 FT-SPK with aromatics. Full compatibility with the existing fleet requires a certain share of aromatic content.

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7 Annex

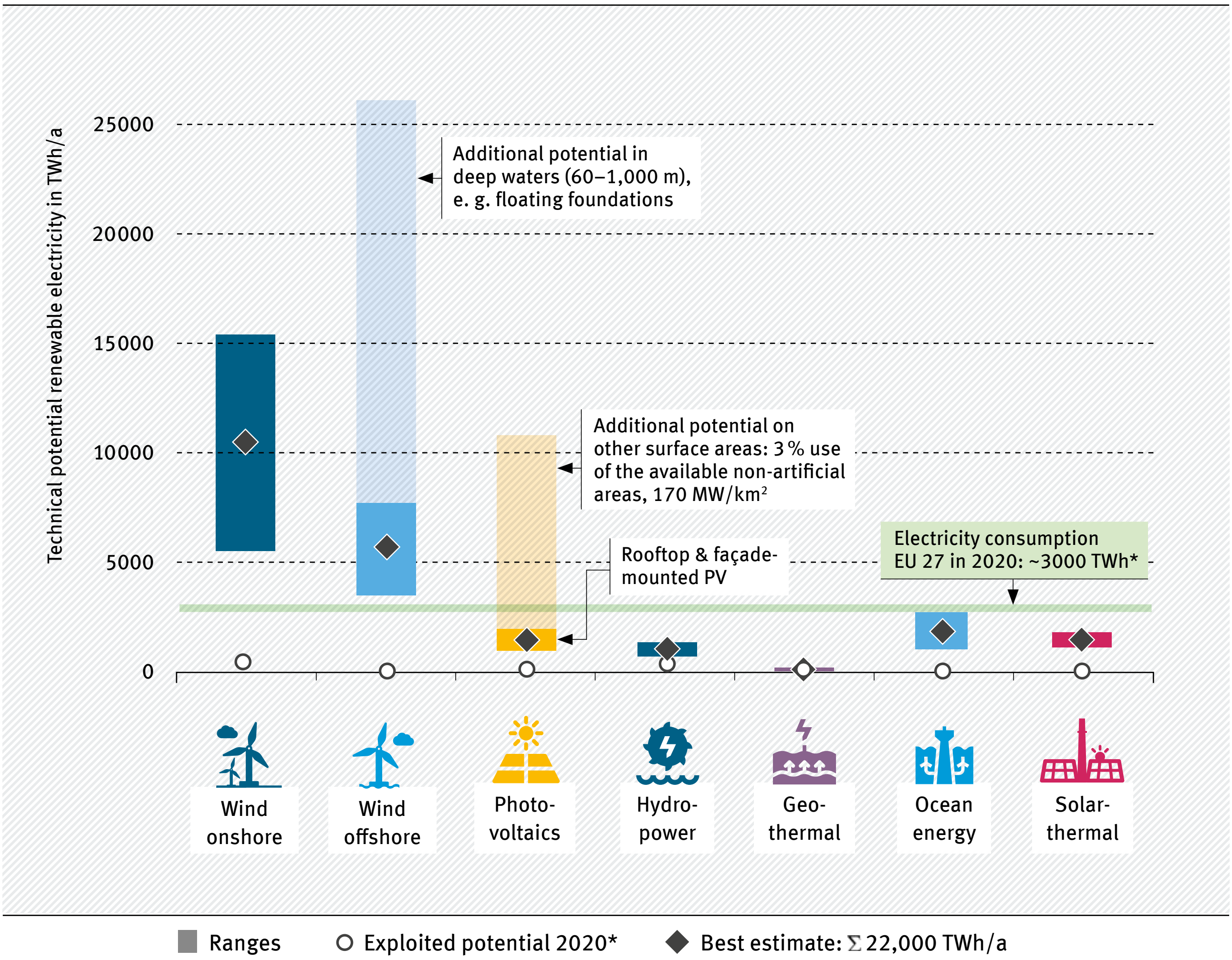
7.1 Bandwidths of renewable electricity potentials Europe, Germany and world from literature

In this study, the technical production potentials have been collated from different literature sources. Technical potentials are usually significantly lower than theoretical potentials as exclusion areas, such as the built environment (except PV on roof-tops and facades), natural reserves and other areas with restricted use (military areas, aviation infrastructure, etc.) are not taken into account for energy production purposes. On the other end, technical potentials may be further limited if applying cost aspects to the calculation ('economic potential'), and further if additional aspects like social acceptance are taken into account ('realistic' or 'near-term potential').

Figure 15 depicts the bandwidth of technical renewable electricity generation potentials by power source in the example of Europe.

Figure 15

Technical renewable electricity generation potential in Europe



* 2020 data: Eurostat 06/2021, IEA Data Services 10/2021

Source: LBST, based on data from Brauner (2019), Caglayan et al. (2019), EEA (2009), Elavarasan (2019), JRC (2019), Ruiz et al. (2019), LBST (2016), Magagna (2019)

Technically, there are vast renewable electricity generation potential from offshore wind, onshore wind as well as solar power in Europe. Ranges applying for Germany and on a global scale are given in the following, too.

As depicted in Figure 15, the technical potential for wind offshore in Europe is between 3,400 TWh/a (EEA 2009) and 26,500 TWh/a (thereof 18,300 TWh in deep waters 60 - 1,000 m) (JRC 2019). On a global scale, it is estimated to be around 216,000 TWh/year (water depth < 500 m) (Chu & Hawkes 2020). Agora scenarios projecting near climate neutrality by 2050 for Germany assume an installed capacity of 50 to 70 GW of offshore wind in Germany, generating some 200 to 280 TWh of electricity per year (Agora 2020).

The technical potential for wind onshore in Europe is between 5,700 TWh/a and 15,000 TWh/a (JRC 2019). Therein, the technical potential of wind onshore in Germany is estimated to be about 500 TWh/a (Deutsche WindGuard 2020). At the same time, the figure is assessed to be around 211,000 TWh/a on a global level (Chu & Hawkes 2020).

The EU's total potential for solar electricity production is 11,000 TWh/a (based on 170 MW/km² PV and a 3 % use of the available non-artificial areas). Only a small share of this potential consists of roof-top and façade-mounted PV, ranging from 1,200 TWh/a to 2,100 TWh/a (Ruiz et al. 2019). The technical potential of photovoltaics on a global scale is estimated significantly higher: around 900,000 TWh/a (Chu & Hawkes 2020) and is therefore considered to be the energy source with the highest technical potential on a global level. Data for Germany indicates that the potential there is some 250 TWh/a (including limitations through protected areas) according to Brauner (2019). For Europe, the potential from solar thermal power (SOT) plants is in the same order of magnitude like PV on rooftops and façades; SOT potentials could also be exploited using PV systems (but not the other way around as SOT requires high shares of direct solar irradiation, whereas conventional PV does work well with diluted solar irradiation.

The technical potential of hydropower in Europe is between 500 TWh/a and 2,100 TWh/a (Elavarasan 2019), 22 TWh/a for Germany (Brauner 2019), and on a global scale between 13,889 TWh/a and 16,667 TWh/a (Teske et al. 2019).

The technical potential of ocean power (comprising wave and tidal energy) in Europe and worldwide is indicated with 600 – 2,900 TWh/a and 30,700 TWh/a, respectively (Magagna 2019).

The technical potential of geothermal power is considered to be the smallest in the regions investigated. For Europe, Germany and world, it is estimated to be 44 – 82 TWh/a, 0.16 – 20 TWh/a and 277 – 833 TWh/a, respectively (Moriarty & Honnery 2018).

In total, the bandwidth averages give best estimates in the order of 22,000 TWh/a, 1,000 TWh/a and 1,350,000 TWh/a for Europe, Germany and at global scale, respectively.

7.2 Technology Readiness Levels (TRL)

TRL definition

Table 10

Definition of Technology Readiness Levels according to to European Commission (2016)

TRL	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

TRL of PtL key process components

Table 11

Current technology readiness level (TRL) of PtL key technologies

Technology	TRL (today)
Water electrolysis	
Alkaline electrolyser	9
Polymer-electrolyte membrane electrolyser (PEM)	9
High-temperature electrolyser cell (SOEC)	7/8*
CO_2 supply	
CO_2 extraction	
CO_2 from biogas upgrading, ethanol production, beer brewing, …	9
CO_2 exhaust gas	
Scrubber with MEA	9
Scrubber with ‚next generation solvent'	8
Absorption/electro-dialysis	6
Pressure-swing absorption (PSA) / Temperature-swing absorption (TSA)	6
CO_2 from air	
Absorption/electro-dialysis	6

Technology	TRL (today)
Absorption/desorption (TSA)	7-8**
CO_2 conditioning (liquefaction and storage)	9
Synthesis	
H_2 storage (stationary)	9
Fischer-Tropsch pathway	
Fischer-Tropsch synthesis	9
Reverse water gas shift (RWGS)	7***
Hydrocracking, isomerization	9
Methanol pathway	
Methanol synthesis	9
DME synthesis	9
Olefin synthesis	9
Oligomerization	9
Hydrotreating	9

RWGS = reverse water gas shift; SOEC = solid oxide electrolysis cell; TSA = temperature-swing adsorption; MEA = membrane-electrode-assembly
ASTM = American Society for Testing Materials (today: ASTM International)

Source: LBST

* Cell area greater than/up to 100 cm² (greater cell area preferable for plants at scale)
** Higher-capacity plant went onstream only recently; operational experience in hot climate pending
*** For smaller RWGS units (according to technology provider

7.3 Assumptions for the calculation of PtL land requirement

In case of utility-scale photovoltaic (PV) power plants a solar irradiation of 1100 (Lusatia area, Germany), 1900 (Southern Spain), and 2100 kWh (e.g. Ouarzazate, Morocco) per ha and year has been assumed. The efficiency of the PV panel is 20 % and the performance ratio is 83 % (ISE 2021). For a conservative estimation, the PV panel occupancy is equal to one third of the land area (UBA 2016). Single-axis sun tracking is assumed as typical for large-scale PV plants e. g. in MENA region today. The assumptions are conservative, meaning they reflect today's technical performance.

To avoid shading the distance between the onshore wind converters of about four rotor diameter is required (IWES 2013). For wind power in the EU a rated power of 4 MW, a rotor diameter of 150 m and an equivalent full load period of 2690 hours per year as indicated in Deutsche WindGuard (2015) for Germany, 3230 hours per year for Spain as indicated in REVE (2020), and 3600 hours per year for Morocco based on three existing wind farms (Tarfaya wind farm, Akhfennir wind farm, Amogdoul wind farm) have been assumed (for comparison, UBA (2013) found 2440 equivalent full load hours per year for average onshore wind power plants in Germany).

To avoid shading about 360,000 m² of land area per wind turbine is required. The land area requirement for foundation, parking space for the crane, and access roads is much lower lower (UBA 2016). According to Gießen (2015) and Windconcept (2013) the land area requirement per wind turbine ranges between 2500 – 5500 m² and 1200 – 2500 m², respectively. As a result, only about 1.5 % of the land is occupied by the foundation, parking space for the crane, and access roads.

For the calculation of the area specific yield of jet fuel it has been assumed that a PtL plant based on Fischer-Tropsch synthesis with low temperature electrolysis combined with CO_2 from direct air capture located in Germany is applied for the lower limit which represents a location in central Europe. For the upper limit a PtL plant based on the methanol pathway involving low temperature electrolysis and CO_2 from a concentrated source located in MENA region has been applied which represents a location with high solar irradiation or high wind speeds. The near-term well-to-tank efficiency for the PtL plant amounts to 50 % for the methanol pathway combined with CO_2 from biogas upgrading and about 37 % for the Fischer-Tropsch pathway combined with CO_2 extracted from the air.

7.4 Techno-economic data for PtL

Table 12 and Table 13 display the techno-economic data for PtL production via low-temperature electrolysis for three exemplary regions in the near and long-term, respectively. Cost structures comprise the methanol and Fischer-Tropsch pathway assuming direct air capture (DAC) and a concentrated CO_2 source for each.

Table 12

Techno-economic data for PtL production (near term)

	Unit	Methanol pathway		Fischer-Tropsch pathway	
Plant data					
CO_2 source	-	Direct air capture	Concentrated source	Direct air capture	Concentrated source
Electricity input	MW	3350	2735	3652	3050
Fuel output	MW_{LHV}	1368	1368	1368	1368
	t/h	112	112	114	114
	kt/yr	978	978	1000	1000
Efficiency	-	41 %	50 %	37 %	45 %
Investment		2622	2622	2965	2965
Electrolysis	M€				
H_2 storage loading compressor	M€	146	146	165	165
H_2 storage	M€	711	711	804	804
CO_2 supply	M€	881	199	1009	226
Synthesis & conditioning	M€	1522	1522	1506	1506
Total	M€	5880	5198	6448	5665
Specific costs					
Central Europe (Germany)	$€/GJ_{LHV}$	60.4	51.2	66.9	57.3
	€/t	2608	2209	2885	2473
South Europe (Spain)	$€/GJ_{LHV}$	47.7	40.5	52.9	45.4
	€/t	2060	1746	2284	1960
MENA (Morocco)	$€/GJ_{LHV}$	44.5	37.8	52.2	45.2
	€/t	1919	1630	2252	1950

Source: LBST

Table 13

Techno-economic data for PtL production (long term)

	Unit	Methanol pathway		Fischer-Tropsch pathway	
Plant data					
CO_2 source	-	Direct air capture	Concentrated source	Direct air capture	Concentrated source
Electricity input	MW	3061	2446	3325	2723
Fuel output	MW_{LHV}	1368	1368	1368	1368
	t/h	112	112	114	114
	kt/yr	978	978	1000	1000
Efficiency	-	45 %	57 %	42 %	51 %
Investment					
Electrolysis	M€	890	890	1006	1006
H_2 storage loading compressor	M€	146	146	165	165
H_2 storage	M€	711	711	804	804
CO_2 supply	M€	881	199	1009	226
Synthesis & conditioning	M€	990	990	1506	1506
Total	M€	3617	2935	4490	3706
Specific costs					
Central Europe (Germany)	€/GJ_{LHV}	43.4	35.1	50.7	42.1
	€/t	1872	1516	2186	1816
South Europe (Spain)	€/GJ_{LHV}	35.0	28.4	40.8	34.0
	€/t	1816	1508	1762	1467
MENA (Morocco)	€/GJ_{LHV}	33.5	27.2	40.2	33.7
	€/t	1445	1174	1735	1456

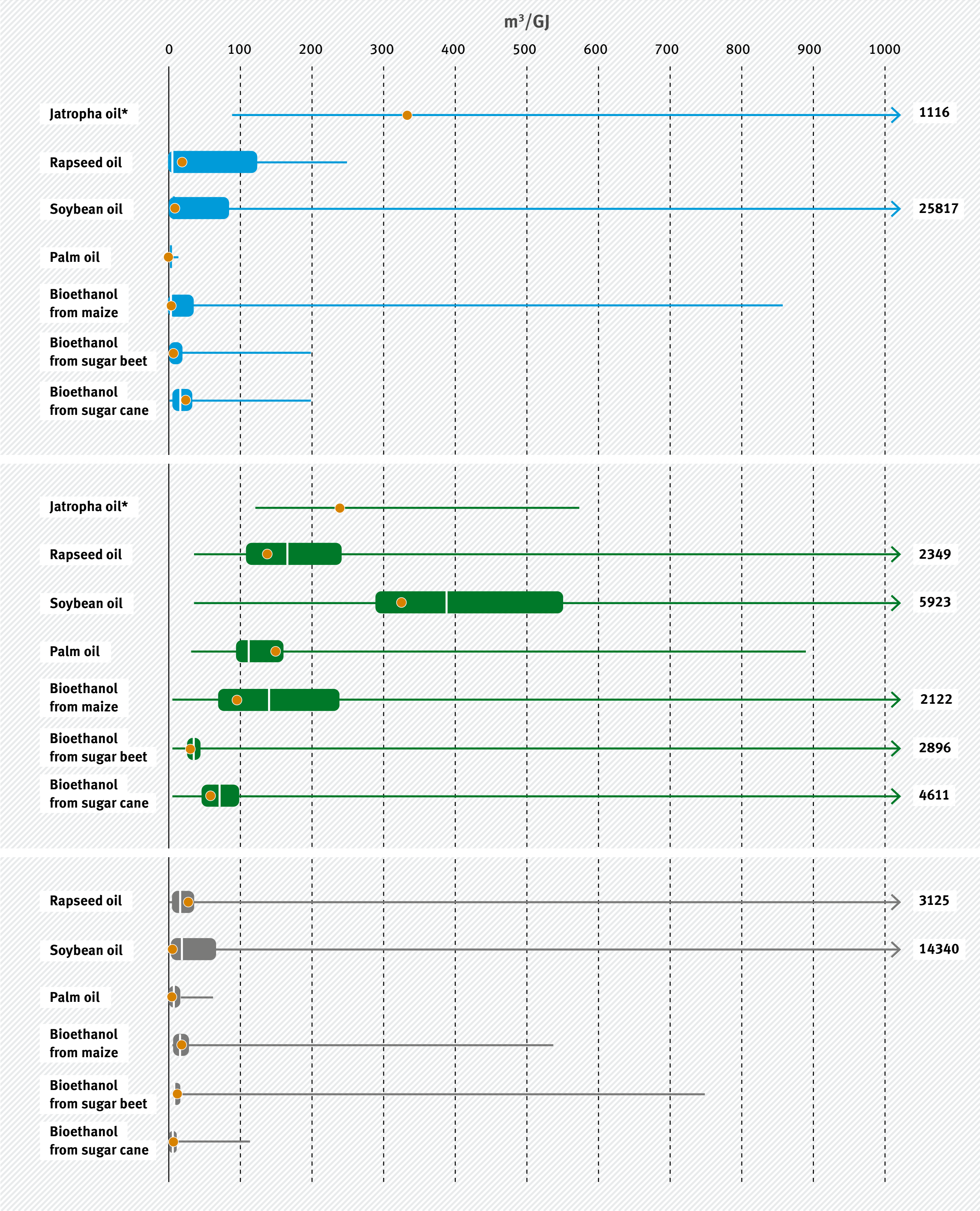
Source: LBST

7.5 Variability of green, blue and grey water demand of biomass-based pathways

To illustrate variations in water use within a biomass-based fuel pathway (influenced e.g. by the local climate and agricultural practices) and differences across selected pathways, Figure 16 shows global variations of water use for a number of feedstocks applied in SAF production based on an assessment by Mekonnen und Hoekstra (2010). The yellow points indicate the global average.

Figure 16

Blue, green and grey water demand of various feedstocks used for SAF production



Top: blue water demand; middle: green water demand; bottom: grey water demand. The box plot illustrates minimum and maximum value as well as first quartile, median and third quartile. The yellow dot indicates the global average.

*limited data range available, therefore quartiles not indicated

Source: BHL, based on data from (Mekonnen und Hoekstra 2010; Gerbens-Leenes et al. 2009)

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AtJ	Alcohol-to-Jet
BtL	Biomass-to-Liquid
CO_2	Carbon dioxide
CSP	Concentrated solar-thermal power
CtL	Coal-to-Liquid
DAC	Direct air capture
FT	Fischer-Tropsch
GHG	Greenhouse Gas
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
LUC	Land use change
MeOH	Methanol
PtG	Power-to-Gas
PtL	Power-to-Liquids
PV	Photovoltaics
RFNBO	Renewable fuels of non-biomass origin
RWGS	Reverse watergas shift
SAF	Sustainable aviation fuels
PEM	Proton Exchange Membrane
SOEC	Solid-oxide electrolysis cells
SPK	Synthetic paraffinic kerosene
SPK/A	Synthesized paraffinic kerosine plus aromatics
TRL	Technological readiness level
TSA	Temperature swing adsorption

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