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Power-to-Liquids
Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel

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Abstract

The 2015 Paris Agreement requires massive greenhouse gas emission reductions in all sectors by mid-century. Renewable fuels are a major building block to achieve substantial absolute emission reductions in aviation. This study gives an introduction into the novel concept of producing renewable jet fuel using renewable electricity, so-called Power-to-Liquids (PtL). The PtL production pathways and the drop-in capability of the resulting jet fuel are explained and their comparative performances are discussed in terms of greenhouse gas emissions, energy efficiencies, costs, water demand and land requirements.

The study is directed towards industry, politics and non-governmental actors in aviation; experts in aviation emissions and renewable jet fuels; and the interested public in the field.

The project underlying this report was supported with funding from the German Environment Agency. The responsibility for the content of this publication lies with the authors.

Foreword

At the 2015 United Nations Climate Change Conference (COP 21) in Paris the contracting parties agreed to limit global warming to well below 2°C above pre-industrial levels. Additionally, efforts should be made to limit the increase to 1.5°C. In order to comply with these targets, the still growing emissions of greenhouse gases have to be reduced drastically and as soon as possible. Finally, a move should be made towards an almost carbon-neutral global society and economy – including aviation – in the second half of the 21st century. Overarching national, European and international frameworks should be developed further, particularly those in place for climate protection, to address the role of aviation.

The German Environment Agency (UBA) has for several years been researching appropriate, effective ways of implementing targets on arresting climate change in a highly industrialized and developed nation like Germany. With the study 'Greenhouse gas-neutral Germany 2050' UBA demonstrated that a greenhouse gas-neutral Germany can largely be achieved using technical measures (UBA 2014). It was shown that transport emissions – including Germany's share of international aviation and shipping – have to be reduced to zero until 2050 in order to comply with the target of a 95 % reduction of greenhouse gases compared to 1990 levels. In the scenarios the energy demand for transport is satisfied by using renewable electricity directly and by using power-generated fuels made with renewable electricity.

Aviation plays an important role regarding the achievement of climate protection targets and will have to significantly contribute to the overall transformation of the society. Its huge expected growth rates, as well as reductions of greenhouse gas emissions in other sectors, will cause a further increasing share of the overall emissions for aviation. The potentials to directly use renewable electricity in commercial aviation are limited due to technical reasons. Fuels made from renewable electricity, renewable carbon dioxide and water are a promising alternative, allowing for near-zero net greenhouse gas emissions, and are therefore able to reduce the absolute greenhouse gas emissions from aviation. These fuels can be generated through the so-called "Power-to-Liquids" process and as a result of their comparatively small greenhouse gas footprint they can contribute to achieving the targets of the International Civil Aviation Organization (ICAO) regarding carbon-neutral growth from 2020 on and industry goals for the aviation sector.

Main ideas on the integration of PtL have been assessed in 2016's UBA position paper entitled 'Integration of Power to Gas/Power to Liquids into the ongoing transformation process' (UBA 2016). In particular the challenges for the integration and further development of this technology in the ongoing transformation process of the energy system are covered with focus on issues that should be addressed during the next few years.

The present study, 'Power-to-Liquids – Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel', focuses on aviation and investigates the PtL process as one major pillar of the energy supply in a greenhouse gas-neutral transport world. Technical, economic, and environmental aspects and potentials are discussed comprehensively. PtL is compared with other pathways for renewable jet fuel production. The study was conducted by the Ludwig-Bölkow-Systemtechnik GmbH and Bauhaus Luftfahrt e.V. on behalf of the German Environment Agency.

Dr. Harry Lehmann,
Head of Division I "Environmental Planning and Sustainability Strategies",
German Environment Agency

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Abbreviations

ATAG	Air Transport Action Group
bbl	Barrel (1 bbl (imperial) = 159.11 liters)
BHL	Bauhaus Luftfahrt e.V.
BtL	Biomass-to-Liquid
CO	Carbon monoxide
CO_2	Carbon dioxide
CtL	Coal-to-Liquid
d	Day
FT	Fischer-Tropsch
FT-SPK	Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene
GHG	Greenhouse Gas
GJ	Gigajoule
GtL	Gas-to-Liquid
H_2	Hydrogen
ICAO	International Civil Aviation Organization
kWh	Kilowatt-hour
LBST	Ludwig-Bölkow-Systemtechnik GmbH
LHV	Lower heating value
MeOH	Methanol
MJ	Megajoule
MWh	Megawatt-hours (1 MWh = 1000 kWh)
PEM	Proton Exchange Membrane Electrolyzer
PM	Particulate Matter
PtL	Power-to-Liquids
SOEC	Solid Oxide Electrolyzer Cell (high temperature)
TRL	Technology Readiness Level
UBA	Umweltbundesamt (German Federal Environment Agency)
WTT	Well-to-Tank
WTW	Well-to-Wake
yr	Year

Executive Summary

What is at stake?
Aviation is at a crossroads. The 2015 Paris Agreement requires massive greenhouse gas emissions reductions in all sectors by the middle of this century. Already in 2009, the International Air Transport Association (IATA) presented the aviation industry's environmental goal, a net reduction in carbon emissions of 50 % by 2050 compared to 2005. That is a mere 35 years looking into the future for a sector with aircraft program times that can easily span over 50 years. Future innovative – or even disruptive – aviation propulsion systems may become important in the long run. However, a drop-in renewable fuel option offering near-zero net greenhouse gas emissions is key in achieving substantial greenhouse gas emissions reductions in aviation. Timing and magnitude indeed matter because it is the emissions integral over time that counts. The later absolute greenhouse gas emission reductions take place, the more disruptive the consequences for the society and the aviation sector are. While greenhouse gas emissions are currently paramount in environmental discussions, future fuel options must provide a robust and high sustainability performance across all sustainability topics relevant to aviation, including, among others, pollutants, high-altitude climate impacts, water demand, or land requirements.

What is Power-to-Liquids?
Power-to-Liquids (PtL) is a production pathway for liquid hydrocarbons based on electric energy, water and CO_2 as resources.

There are two principle pathways to produce renewable PtL jet fuel:

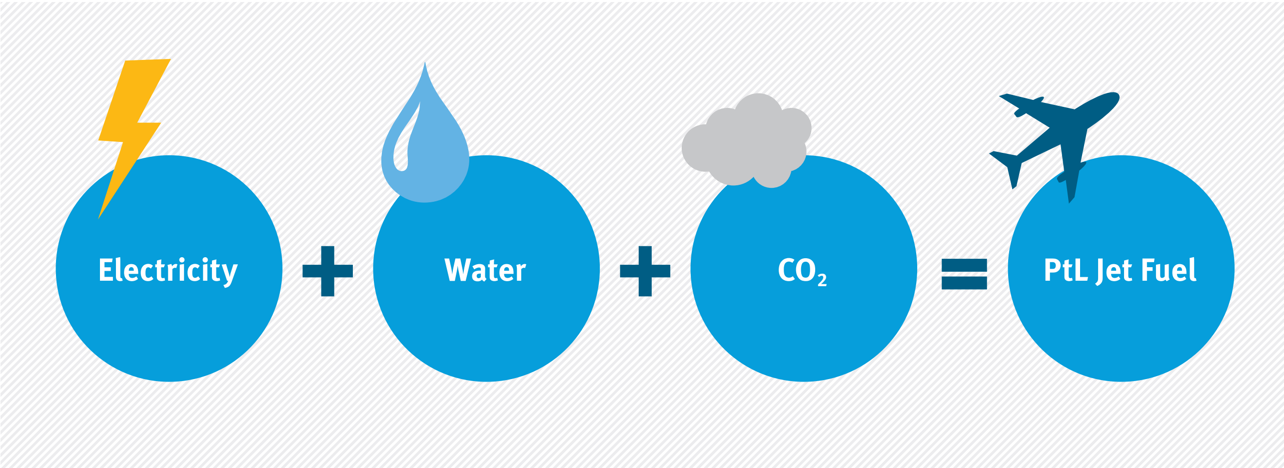
- Fischer-Tropsch (FT) synthesis and upgrading.
- Methanol (MeOH) synthesis and conversion.

PtL production comprises three main steps:

1. Hydrogen production from renewable electricity using the electrolysis of water.
2. Provision of renewable CO_2 and conversion.
3. Synthesis to liquid hydrocarbons with subsequent upgrading/conversion to refined fuels.

Like any other synthesis process, PtL production results in a mix of gasoline, kerosene, diesel, and other fuel products. The product mix may be shifted towards at least a 50 % share of jet fuel components by energy.

High technology readiness
Both PtL pathways (via Fischer-Tropsch or methanol) offer a high level of technology readiness. PtL can be produced from concentrated renewable CO_2 sources using established industrial-scale processes with technology readiness levels (TRL) between 8 and 9 (out of 9). While individual processes have been deployed at large scale, PtL full system integration is currently significantly progressed with the Fischer-Tropsch pathway demonstration plant by Sunfire in Dresden, Germany. Improved processes for CO_2 extraction from air (TRL 6) and high-temperature



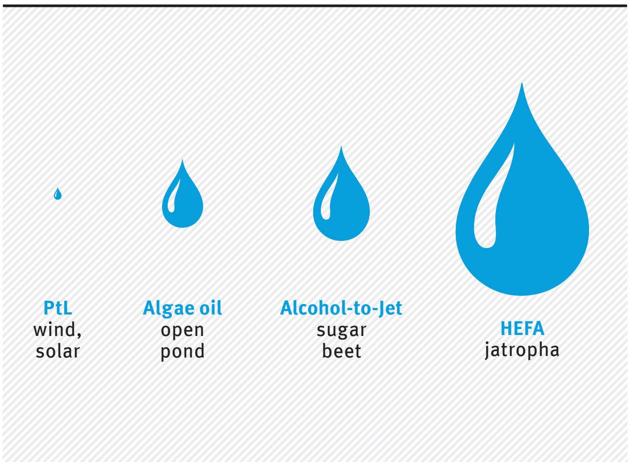
electrolysis (TRL 5) increase the production potential and efficiency, respectively. Renewable electricity costs have dropped significantly in recent years, meriting a fresh look at Power-to-Liquids pathways.

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 is not yet approved.

Environmental benefits of PtL
As this study shows, the environmental benefits of PtL are evident when using electricity, CO_2, and water from renewable sources. Greenhouse gas emissions of PtL can be made near carbon-neutral "well-to-wake" when using renewable electricity and CO_2 from biomass sources or the air. Non-CO_2 high-altitude climate impacts are reduced. PtL water demand is almost negligible and land requirements are much lower compared to biofuels. As a synthetic fuel, PtL offers improved combustion with less pollutants. The following images give indications on the comparative sustainability performance of PtL:

Water demand per liter of jet fuel

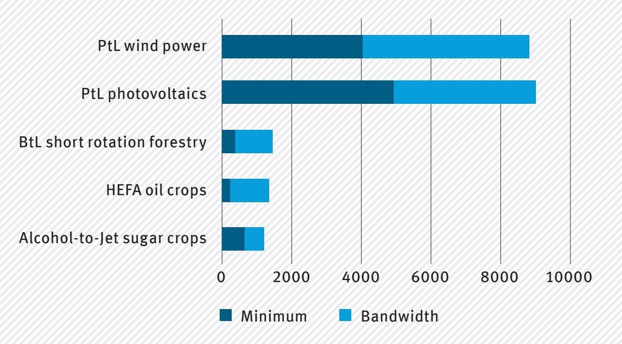
PtL water demand compared to selected biofuels
(volume representation, PtL water demand ~ 1.4 $L_{H_2O}/L_{jet fuel}$)



Source: LBST/BHL, 2016

How far I could fly with the energy from one hectare

Achievable air mileage for an A320neo per ha of land
(km/(ha · yr))



Source: LBST/BHL, 2016

The environmental benefits are paramount in PtL jet fuel from renewable sources lending themselves for closer appraisal by the aviation sector.

Economics and scalability
The main challenge for the short-term deployment of PtL is production costs compared to conventional jet fuel. Cost reductions can be achieved through decreasing renewable electricity costs (wind, solar), increasing efficiencies through improved PtL production processes (high-temperature electrolysis, CO_2 extraction, etc.), and economies of scale and by number.

The main advantage of PtL is huge wind and solar power potentials exceeding global energy demand. PtL thus entails increased energy security, local added value, and a sustainable business perspective for regions with abundant renewable energy.

PtL for aviation – A story bright or bleak?
Like with any other fuel option, the case of PtL jet fuel for aviation cannot be bright white only. The strategic implications of PtL jet fuel are summarized in the following:

Strengths
- Drop-in capability (fuel, logistics, engine)
- High energy density
- Huge global renewable power potentials
- Near-zero GHG emissions potential well-to-wake
- Compared to biofuels
  - lower water demand
  - lower land requirements

Opportunities
- Strengthening the local economy
- Business perspective for regions with large wind and solar power potentials
- Provision of grid ancillary services
- Possible reductions of local and high-altitude emissions

Power-to-Liquids

Challenges/Weaknesses
- Total costs of fuel production
- Renewable CO_2 supply
- No option for zero pollutant emissions

Potential concerns/Threats
- Lock-in of established aircraft technologies (combustion engines)
- Lock-in of conventional CO_2 sources for synthesis
- Acceptance of extensive renewable power plants

Source: LBST

How could PtL jet fuel become part of the solution?

PtL jet fuel produced from renewable electricity and CO_2 should be investigated on equal terms alongside jet fuel from biomass. This includes the support of PtL development and industrial projects. The potential of PtL for significant absolute reductions of the climate impact of aviation should be highly acknowledged and the pathway be strengthened within ICAO's basket of measures for greenhouse gas emission reductions in aviation.

To initiate commercialization of PtL key technologies (UBA 2016), Power-to-Hydrogen from renewable sources could be used to

- improve the greenhouse gas balance of biofuel processes which require hydrogen, e.g. for hydrotreating,
- increase the yields of bioenergy processes that are in excess of carbon, e.g. in the case of digestion or gasification of biomass, and
- substitute fossil hydrogen in crude oil refineries.

The above short-term actions can considerably improve the environmental performance of existing fuel production processes and prepare the ground for the industrialization of PtL pathways at the same time.

What's next?
- Start investigating PtL from renewable sources on equal terms alongside biofuels for aviation. The simple action is, to include PtL in the biofuel-driven investigations of alternative fuels for aviation.
- Strengthen the position of PtL from renewable sources within ICAO's basket of measures to reduce aviation CO_2 emissions.
- Develop and establish sustainability safeguards for renewable PtL jet fuel. Support the development, definition and establishment of robust, verifiable and reportable sustainability criteria and certification schemes for renewable Power-to-Liquids.
- Drive PtL technology competitiveness through ASTM approval of PtL jet fuel produced via the methanol pathway.
- Establish PtL jet fuel demonstration projects, e.g. by improving and expanding existing small-scale PtL demonstration plants in terms of
  - installed production capacity,
  - heat integration of high-temperature electrolysis,
  - innovative processes for CO_2 extraction from air,
  - conversion/upgrading according to jet fuel specifications, or
  - 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. Develop business cases for industrial-scale PtL production to inform discussions about supporting frameworks.

1 Need for renewable fuels in aviation

Protection of the climate represents a challenge of central importance for mankind in the 21st century. At the 2015 United Nations Climate Change Conference (COP 21) held in Paris, the parties agreed on the long-term target of “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels […]”. In order to achieve this goal, a “global peaking of greenhouse gas emissions” should be reached “as soon as possible”, with “rapid reductions thereafter” towards an essentially carbon-neutral global society and economy in the second half of the 21st century (UNFCCC 2015)[1]. This can only be achieved through substantial contributions by all sectors generating greenhouse gas emissions, including international aviation, in particular in light of aviation’s past, current and projected rates of growth.

In response to the need for reducing its greenhouse gas (GHG) footprint, the Air Transport Action Group (ATAG) has published a set of non-binding targets for the aviation industry (ATAG 2012), as illustrated in **Figure 1**. These targets include a cap of the fleet’s net CO_2 emissions through carbon-neutral growth from 2020 on as well as halving the fleet’s annual net CO_2 emissions by 2050 relative to the level of 2005. Even under optimistic scenarios of technological development, it is almost certain that the estimated future growth in air traffic will outpace the expected gains in efficiency. For example, market forecasts of the aircraft manufacturers Boeing and Airbus predict an annual growth rate of 4.5–5 % until 2030 (Boeing 2013a, Airbus 2012). The European Advanced Biofuels Flight Path Initiative expects an annual growth rate of 4.5 % until 2050 (European Advanced Biofuels Flight Path Initiative 2011). On the other hand, targeted gains in fuel efficiency, for example 1.5 % annually until 2020 (ATAG 2012) or even 2 % annually until 2050 (ICAO 2011), are substantially below projected demand growth. The result is a net growth in fuel consumption and, therefore, a growth in direct emissions, instead of achieving the targeted reduction. Future large-scale use of renewable energy carriers is considered as an essential pillar to close this so-called “emissions gap” (see **Figure 1**).

Alternative energy carriers can be categorized with respect to their compatibility with existing aircraft systems and distribution infrastructure (Kuhn 2012). Drop-in capable alternative fuels can be distributed and used within existing architectures. In contrast, the implementation of non-drop-in fuels requires an adaption of the fuel and combustion systems aboard and on ground. Given the fact that aviation represents a global, highly interlinked and very rigidly standardized sector, such an adaption would be associated with extensive efforts and costs. Therefore, non-drop-in alternatives are considered as long-term options under the precondition that an alternative energy carrier provides substantial advantages which justify the required implementation efforts.

Generally, liquid hydrocarbon fuels offer a number of advantageous properties, a foundation that has facilitated the successful use of kerosene fuels in aviation for decades. In particular the combination of energy density (energy per volume), specific energy (energy per mass), fuel transport and storage properties and costs of conventional (i.e. based on crude oil) kerosene is unrivaled by any alternative non-drop-in energy carriers for aviation considered and researched to date.

Consequently, current efforts in research, industrial development and deployment are focused on renewable drop-in replacements for conventional jet fuel, that is, fuels that resemble the advantageous chemical and physical properties of conventional jet fuel but offer a superior environmental performance. 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, with a focus on (but not restricted to)

1 The timing to achieve full carbon-neutrality is subject the reduction pathway taken. The slower the sustainable development pace is in the near future, the more progressive the transition will have to become later on to limit global temperature rise. If progress is slow in the short to mid-term, carbon-neutrality will in fact be required before 2050.

greenhouse gas emissions, a set of key performance indicators for alternative jet fuels can be concluded:

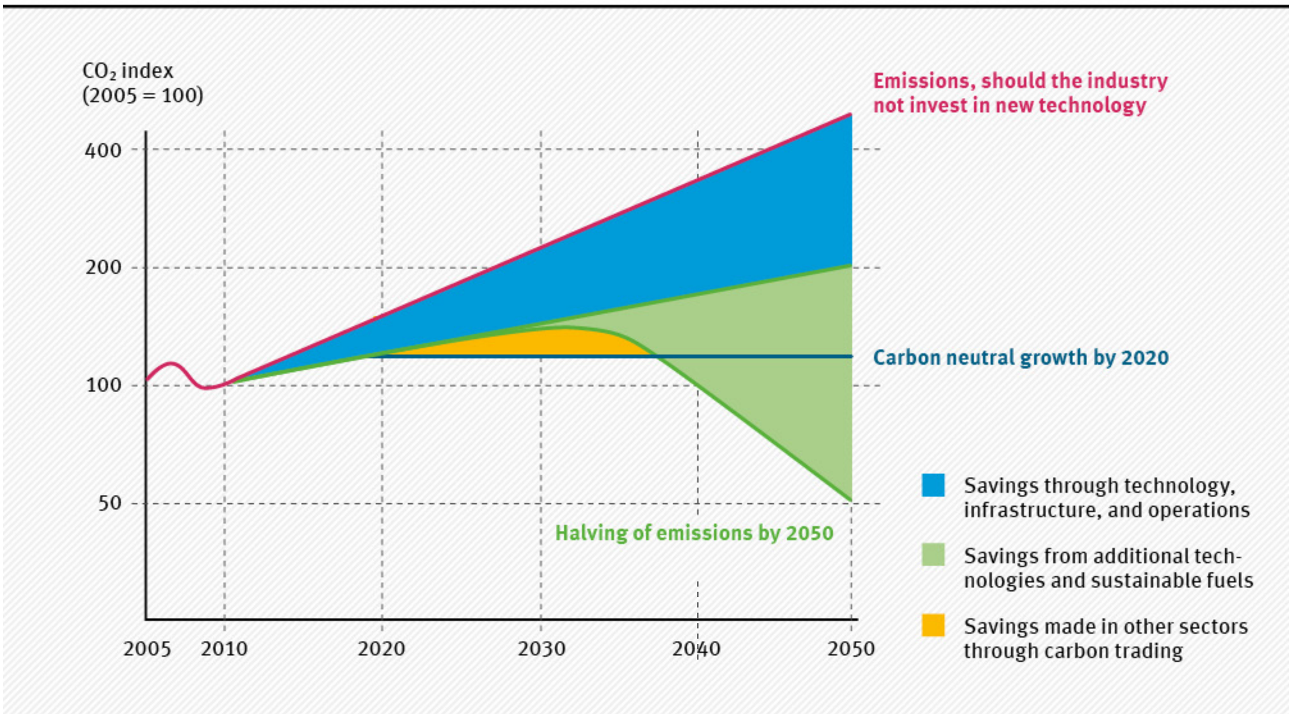
- Largely reduced specific greenhouse gas emissions on a lifecycle basis
- At least similar (better lower) specific air pollutant emissions
- Energy-efficient production
- Resource-efficient production, e.g. in terms of water consumption and land requirement
- Large sustainable production potential
- Economic competitiveness and local added value

The central objective of the present background paper is to convey a brief but comprehensive picture of the potentials of PtL fuels, i.e. fuels produced from renewable electricity, carbon dioxide and water, as renewable but non-biogenic[2] drop-in replacement for conventional jet fuel.

In the following sections, basic principles of the PtL production technology are described and the present state of development and bottlenecks of this technology are discussed. Furthermore, PtL fuels are evaluated against the key requirements listed above, and compared with other production technologies for renewable jet fuels.

Figure 1

Illustration of greenhouse gas emission reduction targets of the aviation industry



Source: Adapted from ATAG (2012)

2 Power-to-Liquids: The basic principles

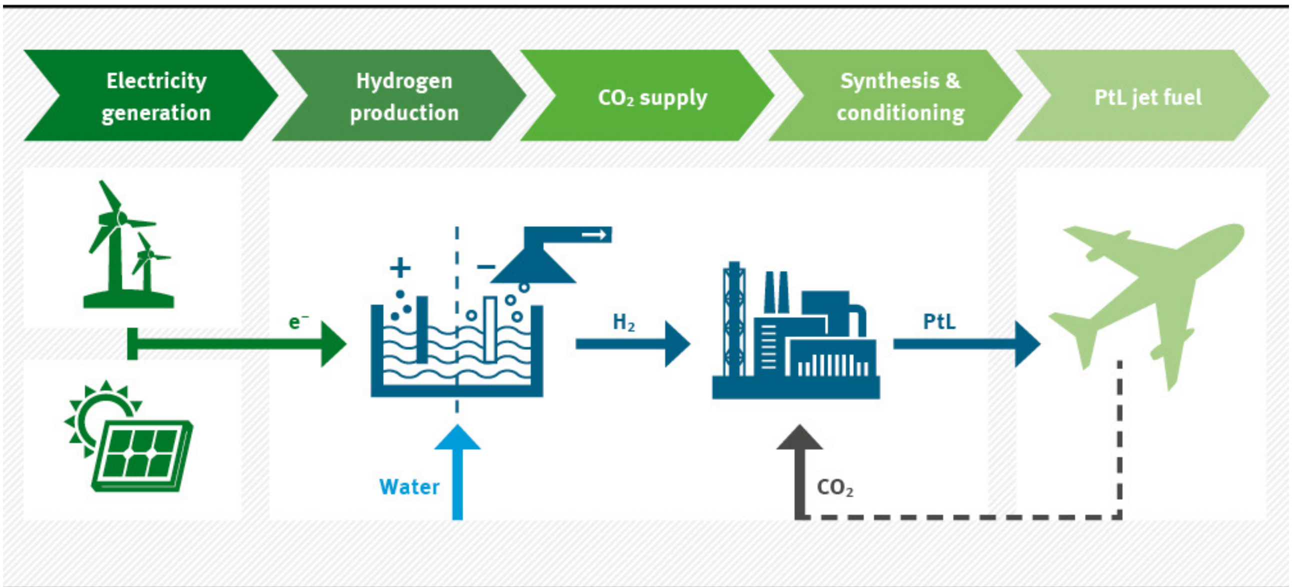
2.1 How liquid fuels are made from renewable power

It is not yet commonly known that liquid hydrocarbons, such as jet fuel, can in fact be produced from renewable power. This concept is called 'power-to-liquids' (PtL) which has received increasing attention lately, e.g. through several scenarios analyses (UBA 2013, IFEU et al 2016, LBST 2016), and a position paper regarding possible roles for synthetic fuels based on renewable electricity (UBA 2016). The basic steps in the value chain and adherent process elements are depicted in **Figure 2** for the production of PtL jet fuel.

2 i.e. not based on biomass feedstock

Figure 2

Power-to-liquids production (generic scheme)



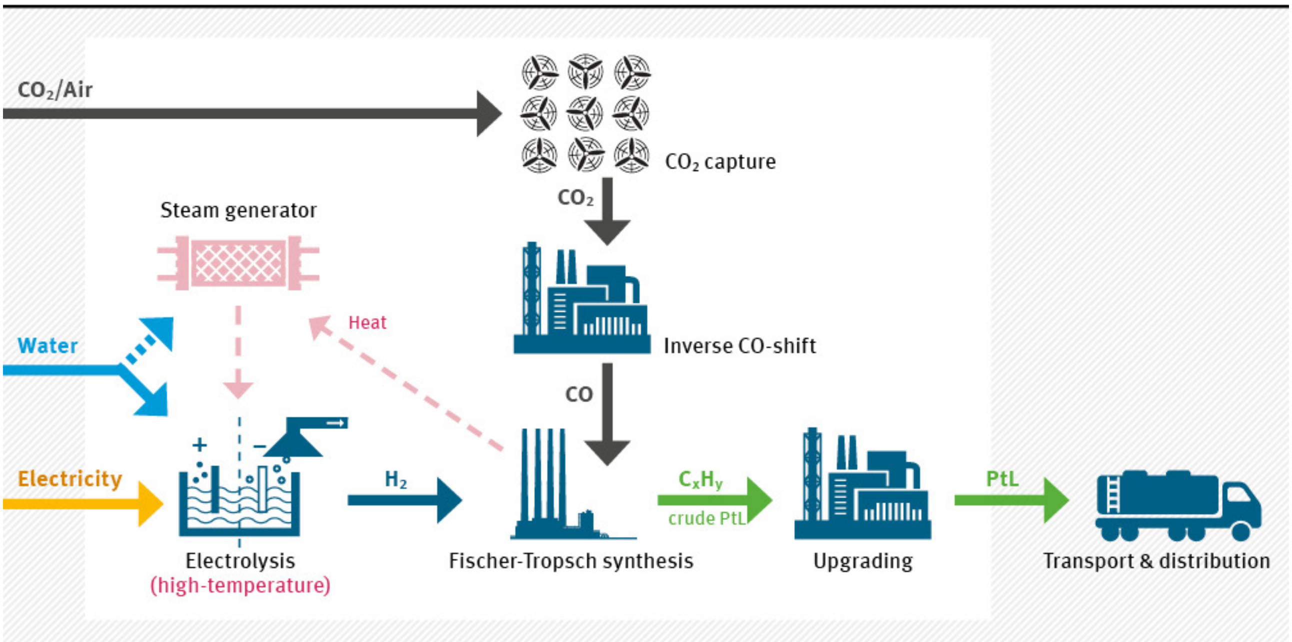
Source: LBST

Renewable electricity, water and carbon dioxide (CO_2) are the main constituents. Wind and solar power are used to produce hydrogen via water electrolysis. Liquid hydrocarbons are synthesized from hydrogen and carbon dioxide and further refined to specified fuels.

Among the PtL fuel chain, there are two main production pathways, the Fischer-Tropsch (FT) pathway and the methanol (MeOH) pathway. The energy efficiency – the energy effort required to produce a unit of jet fuel – of the Fischer-Tropsch and the methanol pathway are about the same. Both pathways are highly sensitive regarding how well waste heat from syntheses can be recuperated and used in, e.g., electrolysis or CO_2 provision. Energy efficiencies for various PtL process configurations are depicted in Section 3.2. Further pathway-specific characteristics are described in the following.

Figure 3

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



Source: LBST

Fischer-Tropsch pathway
The Fischer-Tropsch pathway to synthetic jet fuel is commonly used in biomass-to-liquid (BtL), gas-to-liquid (GtL) and coal-to-liquid (CtL) processes. Instead of biomass, natural gas, and coal, respectively, hydrogen from water electrolysis is used (**Figure 3**).

The Fischer-Tropsch synthesis requires carbon monoxide. In synthesis pathways like BtL and CtL, this is provided from the gasification of biomass and coal respectively. In the FT-PtL case, CO_2 from concentrated sources or extracted from the air is used. The CO_2 is converted to CO via an inverse CO-shift reaction using the reverse water gas shift process.

The electricity demand for high-temperature steam electrolysis using a solid oxide electrolysis cell (SOEC) is significantly lower compared to the electricity demand for low-temperature electrolysis of water. In the case of high-temperature electrolysis, waste heat (220–250°C) from the exothermic Fischer-Tropsch synthesis is used for steam generation, thus lowering the electricity demand.

High-temperature electrolysis may furthermore allow for co-electrolysis of steam and CO_2, producing hydrogen and carbon monoxide in a single step. In this case, an inverse CO-shift process step is not needed. However, co-electrolysis is subject to further research and technology validation. For a conservative estimation, co-electrolysis is not considered in this study.

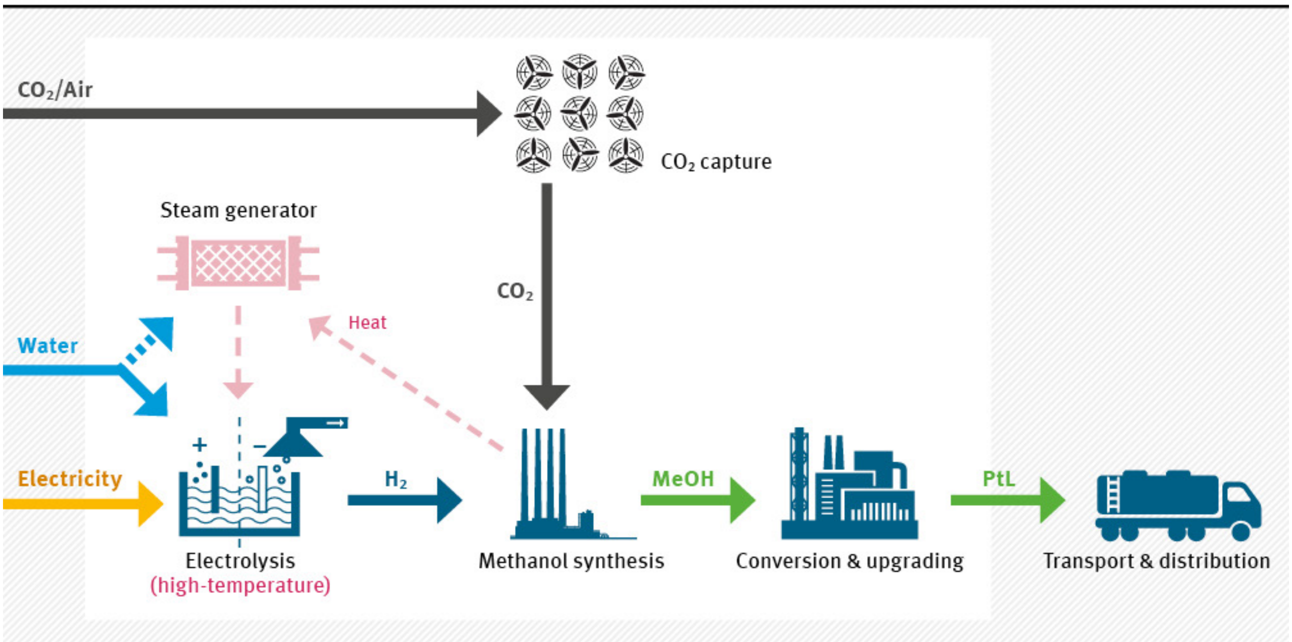
Upgrading the FT-derived crude product to jet fuel and other hydrocarbons comprises several process steps, notably hydrocracking, isomerization, and distillation. These processes are commonly used today at large scale in crude oil refineries as well as in CtL and GtL plants. The share of products from the Fischer-Tropsch synthesis suitable for jet fuel use is about 50 to 60 % (by energy). Oligomerization can be applied for the processing of the C3 and C4 fraction from Fischer-Tropsch synthesis to increase the share of liquid hydrocarbons and to meet the Jet A-1 specifications (de Klerk 2011).

Fischer-Tropsch synthetic paraffinic kerosene is ASTM approved up to 50 % jet fuel blends.

Methanol pathway
An alternative pathway for the production of liquid hydrocarbons, including jet fuel, is via the intermediate product methanol. The pathway can build on industrially proven processes which have already been used for decades in various large-scale applications, such as natural gas reforming and synthesis to methanol (including methanol-to-gasoline conversion in some cases). The production pathway for the PtL methanol pathway is depicted in **Figure 4**.

Figure 4

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



Source: LBST

If high temperature steam electrolysis is applied, the heat from the exothermal methanol formation and other synthesis reactions in the production pathway can – analogous to the Fischer-Tropsch pathway – be used for steam generation. The electricity input for hydrogen production is lowered significantly and the overall power-to-fuel conversion efficiency increased.

For the synthesis reaction to methanol both, CO and CO_2, can be used. A reverse water gas shift process or co-electrolysis of steam and CO_2, as in case of the FT pathway, consequently not a necessity.

Conversion and upgrading of methanol to jet fuel and other hydrocarbons comprises several process steps, notably DME synthesis, olefin synthesis, oligomerization, and hydrotreating.

Gasoline produced via the methanol pathway is compatible to conventional gasoline used in cars. However, no jet fuel has yet been produced via the methanol pathway and technical approval of this pathway according to ASTM D7566 is pending. The necessary process steps are available, however, as they are being used at large-scale in refineries today.

Options for fit-for-purpose plants

There is a host of technology and value chain options available today to design PtL production facilities that are best suited with respect to local conditions.

Power-to-hydrogen options include alkaline electrolyzer, polymere electrolyte membrane (PEM) electrolyzer, and especially the solid-oxide electrolysis cell (SOEC). In order to de-couple a (fluctuating) renewable power supply from rather continuous hydrocarbon synthesis and upgrading, buffer storage of hydrogen is needed. Established hydrogen storage options are, among others, spherical pressure vessels, storage pipes, and salt caverns.

Possible CO_2/CO sources include

- extraction from air, where various processes are available, both established (small-scale) and under development (highly efficient);
- from concentrated renewable sources (biogas upgrading, sewage plants, ethanol plants, exhaust gases from bioenergy use, etc.);
- and from industrial sources (exhaust gas from steel plants, cement production, etc.).

For a conservative estimation and to operate CO_2 extraction in times when there is ample renewable power available, we consider a CO_2 buffer storage and purification by means of CO_2 liquefaction in this study.

2.2 Drop-in capability of power-to-liquid fuels

For safety reasons, aviation is a sector with rigid national and international standards and specifications. This also applies to fuels to be used in aircraft. The compatibility with these specifications is of crucial importance for alternative jet fuels, as the procedure of technical approval represents one of the main barriers to be overcome for any new fuel entering the market.

The most important specifications for jet fuel for civil aviation are listed in the ASTM D1655[3] and DEF STAN 91-91[4] standards. These standards have evolved over the past decades, however always under the assumption that fuels are produced from crude oil. In response to recent interest in synthetic fuels from various alternative sources, the new specification ASTM D7566[5] has been developed, specifically listing requirements for jet fuel containing synthesized hydrocarbons. It also defines approved types of synthetic fuel components and, in particular, specific production technologies.

Meanwhile, several types of synthetic fuels have been approved according to ASTM D7566. The first in this line, Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene (FT-SPK) successfully passed the procedure in 2009 and can now be used in blends of up to 50 % with conventional jet fuel. Annex A1 of ASTM D7566 defines FT-SPK synthetic blending components as “wholly derived from synthesis gas via the Fischer-Tropsch (FT) process using iron or cobalt catalyst”. This definition would also include PtL fuels produced via the FT pathway, as long

3 ASTM D1655: *Standard Specification for Aviation Turbine Fuels*, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States
4 Ministry of Defence, Defence Standard 91-91 (DEF STAN 91-91): *Turbine Fuel, Kerosine Type, Jet A-1. NATO Code: F-35. Joint Service Designation: AVTUR*
5 ASTM D7566: *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States

as iron or cobalt catalysts are used in the FT process and the fuels produced meet the chemical and physical specifications. In this respect, FT-derived PtL jet fuel would not need to be newly approved and jet fuel blends containing FT-SPK from PtL processes can be considered drop-in capable.

In case of PtL kerosene derived via the methanol pathway, prior approval for use in commercial aviation according to ASTM D7566 would be required. PtL jet fuel derived through the methanol pathway consists of more than 90 % iso-paraffines which have good cold flow properties. Oligomerization (a process applied in the methanol pathway) at higher temperatures in the presence of a zeolite catalyst enables generation of aromatics as side products. In this way it is potentially possible to operate a PtL plant so that a fully drop-in capable jet fuel is yielded, as such meeting all ASTM D 7566 specifications, in particular the requirements of a minimum share of 8 % of aromatic compounds (de Klerk 2011). Overall, it can be expected that PtL fuels obtained via the methanol pathway will prove similarly suitable as synthetic blending component in jet fuels as Fischer-Tropsch-derived products.

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

3.1 Technological maturity of power-to-liquids production

The technological maturity of the individual process steps along power-to-liquid pathways is far more advanced than commonly assumed. However, proof-of-concept of an integrated PtL value chain, from renewable electricity and CO_2 to readily refined products, is pending. Such proof-of-concept would provide certainty to planners, users, and investors.

Table 1 gives an overview over the technological maturity of renewable fuel production pathways using the concept of 'Technology Readiness Levels' (TRL).

Table 1

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

Jet fuel production pathway	Technology Readiness Level (today)	Critical element (e.g. determining bandwidth bottom)
PtL	**5–8**	**CO_2 extraction from air (TRL 6)**
Fischer-Tropsch (low-temp)	6	reverse water gas shift (RWGS)
Fischer-Tropsch (high-temp)	5	high-temperature electrolysis (SOEC)
Methanol (low-temp)	8	ASTM approval, final conversion
Methanol (high-temp)	5	SOEC, ASTM approval, final conversion
BtL	**5–9**	**Gasifying feedstock other than wood**
Fischer-Tropsch pathway	5–9	
Methanol pathway	5–8	ASTM approval, final conversion
HEFA (Hydroproccessed Esters and Fatty Acids)	**4–9**	**Feedstock**
Used cooking oil	9	quantity, logistics
Palm, rape seed	9	sustainability, quantity
Algae	4–5	reactor, extraction
HTL (Hydro-Thermal Liquefaction)	**4–6**	**Feedstock**
Wastes/residues	6	quantity, structure
Algae	4	reactor, extraction, conversion
AtJ (sugar, starch) (Alcohol-to-Jet fuel)	**5–9**	**Feedstock quantity**
SIP (sugar) (Synthesized Iso-Paraffins)	**7–9**	**Feedstock quantity**

Source: LBST

The relatively advanced maturity of the PtL technology is due to the fact that processes entailed with PtL production, like synthesis and upgrading, correspond to large-scale fuel synthesis of fossil feedstock in the context of coal-to-liquids (CtL) and gas-to-liquids (GtL). South African Sasol's CtL kerosene was for a long time the only drop-in alternative fuel approved for use in aviation. The bulk quantities of CtL produced in South Africa over decades give confidence regarding key parts of the PtL production chain.

Taking a closer look at electrolysis, notably alkaline technology, shows that this technology has been used in industry for many decades (TRL 9). Emerging electrolyzer technologies still need some (polymer membrane, TRL 8) or major (solid-oxide electrolysis, TRL 5) technological progress. All electrolyzer technologies have in common that only single-digit MW_e plant capacities are currently available for clustering to larger PtL production plants. They may very well serve short-term PtL production demonstration needs. Alkaline electrolyzer plants with capacities exceeding 100 MW have already been operated in the past (Smolinka et al 2012, p 14). Thanks to power-to-gas projects currently mushrooming all over the world, electrolyzer manufacturers are again stepping up the development pace for emerging electrolyzer technologies, electrolyzer unit production capacities, and capabilities for electrolyzer volume manufacturing.

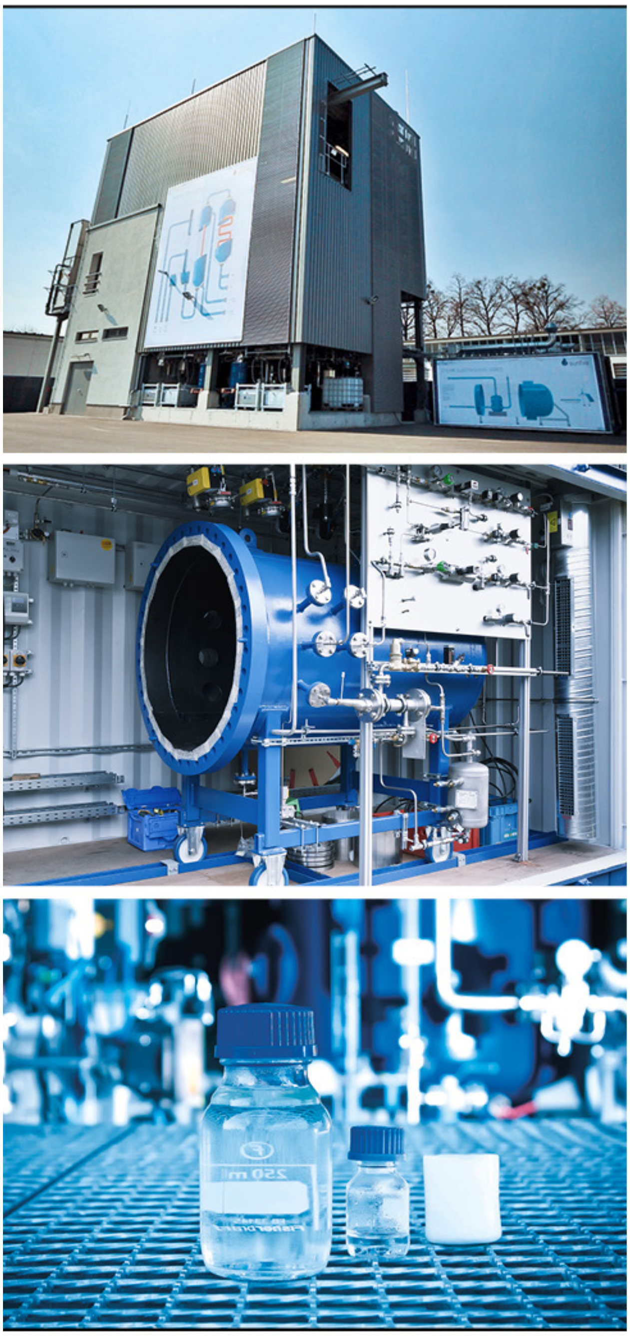
For the supply of CO_2 different sources and processes are available, ranging from conventional scrubbing processes and pressure swing adsorption for CO_2 extraction from biogas upgrading (TRL 9) to novel electro-dialysis or temperature-swing absorption processes for CO_2 extraction from air (both TRL 6). Processes for the extraction of CO_2 from air have to be scaled-up over time as this CO_2 supply option is required for bulk PtL production in the long-run.

Existing PtL demonstration plants

So far, no pilot/demonstration plant for the production of power-to-kerosene is in operation. However, an almost complete PtL pathway with diesel as a final product is being demonstrated by the company Sunfire, see **Figure 5**. In autumn of 2014, the demonstration plant was inaugurated in Dresden (Germany). The installed production capacity is about 1 barrel per day of crude PtL from Fischer-Tropsch synthesis. The only 'missing link' from the perspective of aviation is the upgrading to jet fuel using conventional refinery processes. The concept comprises a high-temperature (solid-oxide) electrolyzer using excess heat from Fischer-Tropsch synthesis. Electricity demand is thus reduced, increasing the PtL production efficiency (fuel output vs. electricity input).

Figure 5

Sunfire PtL demonstration plant (top) using high-temperature electrolysis (middle) for the production of Fischer-Tropsch crude (bottom)



Sources: *top:* sunfire GmbH Dresden/CleantechMedia; sunfire GmbH Dresden/renedeutscher.de

Figure 6 shows a power-to-methanol demonstration plant that has been in operation since 2012.

Figure 6

Power-to-methanol production plant (4000 t/yr, merchant methanol as fuel, e.g. for blending with gasoline, and as chemical feedstock e.g. as input to biodiesel production) using renewable power and CO_2 from geothermal sources, engineered and operated by Carbon Recycling International at Svartsengi, Iceland

Source: ThinkGeoEnergy, Licence CC BY 2.0, 2012

The power-to-methanol plant depicted in **Figure 6** and a smaller demonstrator by Swiss company Silicon Fire are fully integrated up to the point of methanol provision. 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 TRLs in Annex **Table 10**). However, an integrated process chain for the purpose of middle-destillate (diesel, jet fuel) production has not yet been demonstrated. In fact, it would be a logical next step to complement an already existing or upcoming power-to-methanol production plant with a methanol-to-jet fuel step.

3.2 Energy efficiency

Table 2 depicts the efficiency of the production of PtL, differentiated by the CO_2 source and the electrolyzer technology applied.

As can be seen from **Table 2**, two parameters are significantly influencing the energy efficiency of PtL production 'well-to-tank': the CO_2 source and the process heat integration. If a local source of concentrated CO_2 is available – such as biogas upgrading or exhaust gas streams of wood burning for heat (and power) – the energy efficiency is some 10 %-points higher compared to PtL production with CO_2 extraction from the air. Using high-temperature electrolysis and excess heat from the synthesis reaction improves energy efficiency by another 10 %-points compared to using low-temperature electrolysis.

The energy efficiencies of PtL production pathways investigated in this study can be as low as 38 % and as high as 63 % 'well-to-tank', subject to the combination of CO_2 source and electrolyzer technology. **Table 2** is valid for both the PtL Fischer-Tropsch and the methanol pathway, as the difference in the energy conversion efficiency is negligible.

High energy efficiency is relevant in so far as it directly impacts the economics of fuel production and also for reasons of public acceptance of large scale renewable power plant deployment. However, efficiency may not be the dominating issue; provided that renewable electricity is used, other key performance parameters may be paramount for an adequate appraisal of PtL jet fuel against alternative fuel options as the following sections will show.

3.3 Greenhouse gas emissions

According to (LBST 2016) and (JEC 2014) the overall greenhouse gas emissions for production, transportation, distribution and dispensing of PtL from renewable electricity and CO_2 are about 1 g CO_2 equivalent per MJ of final fuel. Since renewable electricity and CO_2 are used for jet fuel production, greenhouse gas emissions only occur at transportation, distribution and dispensing.

Greenhouse gas emissions from the construction of power stations, fuel production facilities, and vehicles

Table 2

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

Pathway*	PtL production efficiency today → improved, using CO_2 from different sources		
	Air	Exhaust gas, e.g. wood burner	Fermentation, e.g. biogas upgrading
PtL with low-temperature electrolysis	38 % → 41 %	47 % → 51 %	48 % → 53 %
PtL with high-temperature electrolysis	45 % → 46 %	60 % → 61 %	62 % → 63 %

* Differences between the Fischer-Tropsch and the methanol pathway are negligible.

Source: LBST

are often not included in life-cycle assessments of transportation fuels. Including the construction of power stations and the PtL plant the greenhouse gas emissions for the production of PtL amount to 11 g and 28 g CO_2 equivalent per MJ of final fuel when using electricity from wind and PV in Germany, respectively, according to a recent life-cycle assessment of the Sunfire PtL demonstration plant by (LBP 2015). In that study, high temperature electrolysis with downstream Fischer-Tropsch synthesis and upgrading as well as CO_2 extracted from air (direct air capture) using waste heat has been assumed. The GHG footprint of PtL from renewable sources is low compared to alternative jet fuels (see **Table 8**) With an increasing share of renewables in the global supply of energy and materials, GHG emissions from the production of renewable power plants and PtL facilities will further decrease in future.

3.4 Water demand

The net water demand results from the water demand from hydrogen production via water electrolysis and the water generated by the synthesis reaction and further downstream processing steps. Water is a feedstock for PtL production. The amount of water needed can be estimated based on the overall process stoichiometry.

Jet fuel consists of hydrocarbons with a carbon number distribution between 8 and 16 (8–16 carbon atoms per molecule). Assuming an average carbon number of 11 (corresponding to, e.g., undecane, $C_{11}H_{24}$) results in the following net reaction for the jet fuel production via PtL (for complete reaction schemes, see Section 7.2 in Annex):

$$12\ H_2O + 11\ CO_2 \rightarrow C_{11}H_{24} + 17\ O_2$$

This net reaction is valid for both the Fischer-Tropsch and the methanol pathway.

According to the stoichiometry of the net reaction, 12 moles of water (216.18 g) are required for the production of 1 mole of $C_{11}H_{24}$ (156.31 g). The lower heating value of jet fuel amounts to about 43 MJ per kg, translating into an energy-related theoretical water demand of 0.032 m^3 per GJ of jet fuel.

In reality a product spectrum including gases is generated during Fischer-Tropsch synthesis. It is assumed that 90 % of the Fischer-Tropsch products consist of liquid hydrocarbons. The gases are combusted and used for heat and electricity generation within the plant. During hydrocracking gases are also generated as well as during the conversion of methanol into final fuel (see methanol pathway). As a result, about 0.038 m^3 to 0.040 m^3 of water per GJ of jet fuel or 1.3 to 1.4 liters of water per liter of jet fuel are required.

3.5 Land use

Land requirement is a key performance indicator when assessing the comparative sustainability performance of alternative fuels. There is a host of renewable electricity sources that can be used for the production of PtL, such as photovoltaics (PV), onshore and offshore wind, concentrated solar-thermal power (CSP), etc. As an example, the area-specific yield of PtL-derived jet fuel based on electricity from utility-scale photovoltaic power plants and from onshore wind power has been calculated for comparison with other alternative jet fuel options in Section 4.1. The assumptions are detailed in Annex 7.3.

Table 3 depicts the results in terms of area-specific yield of jet fuel, area coverage (land surface that is not suitable for other purposes (as it is occupied by wind tower foundationS, access roads to power plants, etc.), and resulting achievable air mileage related to gross area. A specific air mileage of about 0.37 km per kg jet fuel has been assumed, based on an Airbus A320neo aircraft.

It should be noted that in the case of wind power more than 95 % of the land area in **Table 3** can still be used for other purposes such as agriculture,

Table 3

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

	Jet fuel* (GJ ha^{-1} yr^{-1})	Area coverage	Achievable air mileage (km ha^{-1} yr^{-1})
PtL from utility-scale PV	580–1070	33 %	4950–9080
PtL from onshore wind	470–1040	2.6–3.4 %**	4040–8860

* Bandwidth resulting from moderate vs. high-yielding power production locations and CO_2 sources available
** 5500 m^2 for foundation, working space and access roads related to a gross land area of 163,216 to 211,600 m^2 per wind turbine

pasture, etc., and less than 1 % of the land area is impervious surface only. Furthermore, it has to be emphasized that PtL production does not depend on the availability of arable land. For example, arid regions with high solar irradiation are not suitable for agricultural use, but offer high potentials for solar power generation.

3.6 Fuel costs

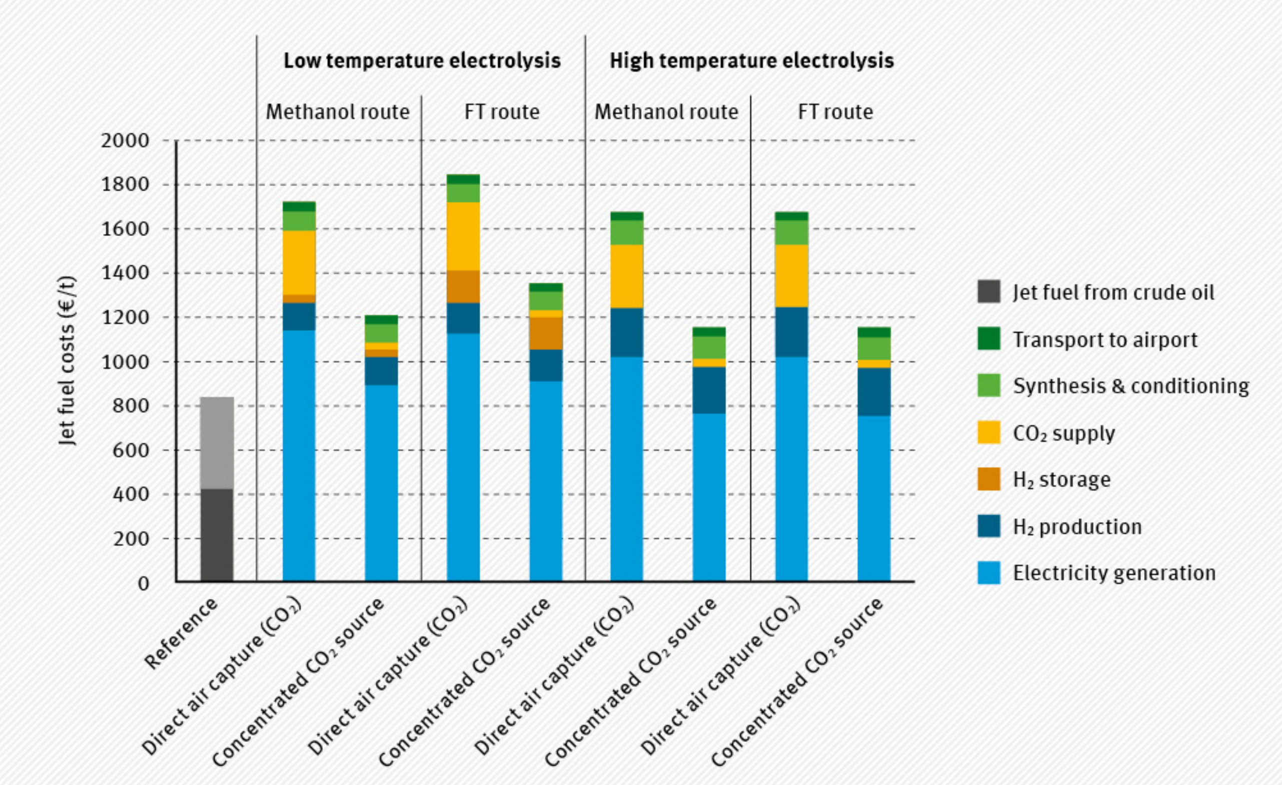
A PtL production pathway described in (LBST 2016) has been selected for the estimation of the long-term costs of PtL-derived jet fuel. It is assumed that the PtL plant is located in a region with high wind speeds. The investment for electricity generation has been derived from an existing wind farm ('Rawson' in Argentina) built in 2012. The rated power of the wind farm amounts to 77.4 MW (Hristova 2015) and the investment amounts to 144 million US$ (Kennedy 2011) leading to about 1500 € per kW of rated power (exchange rate: 0.8 €/US$ in 2012, the year of construction of the wind farm). The investment includes a 295 km HVDC transmission line. The wind farm generates 290 GWh of electricity per year leading to an equivalent full load period of about 3750 hours per year. The cost for operating and maintenance have been derived from (DLR et al 2012) and amounts to 40 € per kW of rated power and year. At an interest rate of 4 % and a lifetime of 20 years the electricity generation costs amount to about 4 cent per kWh of electricity.

Series production of wind turbines can lower the specific investment and, as a result, lower the electricity costs. On the other hand, regions with lower wind speeds than at the location of the Rawson wind farm require a higher hub height and larger rotor diameter for the same electricity yield, leading to higher specific investment and higher electricity costs. Therefore, it has been assumed that the 4 cent per kWh of electricity can be considered as long-term costs of renewable electricity (PV and wind power) at many location of the world.

For the purpose of this study, the technical and economic data for the PtL plant as per (LBST 2016) have been scaled up to a production capacity of 100 kt of liquid hydrocarbons per year. Thanks to economies of scale, this leads to lower specific investment for the direct air capture plant for CO_2 supply and the synthe-

Figure 7

Jet fuel costs projected for future PtL plants in 2050 (jet fuel reference price: 42–95 US$/bbl; renewable electricity costs: 40 €/MWh$_e$; equivalent full-load period: 3750 h$_{eq}$/yr)



Source: LBST

Table 4

Technical and economic data for PtL production via low temperature electrolysis

	Unit	Methanol pathway		Fischer-Tropsch pathway	
Technical key data					
CO_2 source	–	Direct air capture	Concentrated source	Direct air capture	Concentrated source
Electricity input	MW	760	594	729	588
Fuel output	MW_{LHV}	319	319	310	310
	t/h	26.6	26.6	25.8	25.8
	kt/yr	100	100	97	97
Efficiency	–	42 %	54 %	42 %	53 %
Investment					
Electrolysis	M €	140	140	140	140
H_2 storage	M €	3	3	30	30
CO_2 supply	M €	359	45	359	45
Synthesis & conditioning	M €	100	100	94	94
Total	M €	602	288	622	308
Specific costs					
Jet fuel	€/GJ_{LHV}	39.8	28.0	42.7	31.3
	€/t	1719	1206	1841	1352

Source: LBST

Table 5

Technical and economic data for PtL production via high temperature electrolysis

	Unit	Methanol pathway		Fischer-Tropsch pathway	
Technical key data					
CO_2 source	–	Direct air capture	Concentrated source	Direct air capture	Concentrated source
Electricity input	MW	869	645	836	613
Fuel output	MW_{LHV}	405	405	393	393
	t/h	33.8	33.8	32.8	32.8
	kt/yr	127	127	123	123
Efficiency	–	47 %	63 %	47 %	64 %
Investment					
Electrolysis	M €	159	159	159	159
H_2 storage	M €	0	0	0	0
CO_2 supply	M €	433	53	433	53
Synthesis & conditioning	M €	118	118	111	111
Total	M €	710	330	702	322
Specific costs					
Jet fuel	€/GJ_{LHV}	38.7	26.8	38.8	26.5
	€/t	1671	1155	1675	1144

Source: LBST

sis step compared to (LBST 2016). Temperature swing adsorption (TSA) has been used for the capture of CO_2 from air. The equivalent full load period of the PtL plant also amounts to 3750 hours per year. The electricity input of the electrolysis plant amounts to 580 MW if low temperature electrolysis (PEM or alkaline) is used.

Table 4 and **Table 5** show the long-term technical and economic data for the production of jet fuel via PtL involving low and high temperature electrolysis respectively. **Figure 7** shows the long-term costs of PtL jet fuel supply resulting from the cost data as listed in **Table 4** and **Table 5**.

Jet fuel price amounted to 468.5 US$ per t in August 2016 (IATA 2016) or 422 € per t at an exchange rate of 0.90 €/US$ and a crude oil price level of 42 US$/bbl. According to (IEA 2015) future jet fuel price could amount to 95 US$ 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 which has been observed in the past few years, then a significant cost disparity between fossil jet fuel and renewable jet fuel will remain in the future. This is particularly the case for renewable options that offer both, potential scalability and high sustainability performance.

4 Power-to-Liquids in comparison to other renewable fuels

4.1 Sustainability aspects

With regard to the sustainability of renewable fuels, key environmental performance indicators are

- water demand,
- land use, and
- greenhouse gas emissions.

Water demand

Human society is highly dependent on sufficient provision of water. About 70 % of the world-wide water demand is consumed by the agricultural sector, some 20 % by industry and for the cooling of thermal power plants, and some 10 % is used as drinking water. Less than 50 % of the global water consumption is fed by rainwater; the largest part of the water for consumption is taken from reservoirs (lakes, underground). More than 97 % of the global water balance is salt water; less than 3 % is fresh water. The availability of fresh water at sufficient quantity and quality is endangered by over- and misuse and the impacts from climate change (increasing average temperatures, shifting precipitation patterns, more extreme weather conditions). Concerning the 'water energy nexus' (DOE 2014) (IRENA 2015), water is also a critical resource for the provision of electricity from hydro- and thermal power plants and the production of biofuels from energy crops (IEA 2012; p501ff), (IEA 2015; p144).

Against this backdrop and the already high and ever increasing global consumption levels of fuels for transportation, it is thus more than a precautionary move only to map the water demand of different renewable fuel production pathways as collated in **Table 6**.

The aviation sector is by nature truly international. For sustainable development in aviation, water plays an important role when selecting suitable renewable aviation fuels. The net water demand of biofuels is highly sensitive towards the bioenergy feedstock as **Table 6** shows, but also depends on the agricultural production practices (e.g. irrigation) and not least the local climatic conditions at the agricultural site. Biofuels from agricultural and short rotation forestry feedstock require several orders of magnitude – i.e. a factor of 400 to 15,000 – more water than power-to-liquids production from wind electricity and photovoltaics.

The PtL water footprint translates into a net water consumption of 170,000 m³ water per year for a production of 100 kt of PtL per year. Even though this can be considered negligible compared to water demands for biomass feedstock, local water availability and supply options are relevant aspects in the course of the environmental impact assessment typical to planning processes. Such analysis is indispensable if fuel production is foreseen in regions where water availability is critical or already under stress.

Land use

There are two concepts for area demand calculation, the **gross** and the **net land area demand.** The gross land area is relevant e.g. for the question how much area is needed in total to produce a given amount of PtL jet fuel considering the distance between wind turbines to avoid shading. The net land area is relevant for the question how much land is occupied by the installation and cannot be used for other purposes. In case of the biomass derived fuels the gross and net land area are the same. In case of wind power the difference between the energy yield related to net land area and the energy yield related to gross land area is very high, as land coverage usually ranges from 2.5 to 3.5 % (see also **Figure 8**). Nevertheless,

Table 6

Water demand for biofuel and power-to-fuels production

Feedstock/pathway	Green water (m^3/GJ)	Blue water (m^3/GJ)	Sum (m^3/GJ)	Sum ($l_{H_2O}/l_{jet\text{-}fuel\text{-}eq}$)	Reference
Jatropha oil	239	335	574	19914	Weighted global Ø (JRC 2013)
Rapeseed oil	145	20	165	5724	
Soybean oil	326	11	337	11691	
Palm oil	150	0	150	5204	
Sunflower oil	428	21	449	15577	
Ethanol from maize*	94	8	102	3539	
Ethanol from sugar beet*	31	10	41	1422	
Ethanol from sugar cane*	60	25	85	2949	
BtL from poplar**	107	6	112	3892	(Jungbluth et al 2007)
Algae oil (open pond with water recycling)**	0	14	14	497	(Stephenson 2010)
Algae oil (open pond w/o water recycling)**	0	53	53	1839	
PtG hydrogen (wind, PV)	0	0.076	0.076	2.63	This study (LBST)
PtL via FT pathway (wind, PV, CSP***)	0	0.040	0.040	1.38	
PtL via methanol pathway (wind, PV, CSP***)	0	0.038	0.038	1.33	

Green water: Precipitation on land that is stored in the vegetation, in the soil, or stays on top of the soil
Blue water: Water consumption from surface and groundwater
* Similar performance assumed as for direct sugar-to-hydrocarbons conversion, e.g. Amyris-Total 'Farnesane'
** In moderate climate zones, e.g. Europe, Northern USA, Southern Canada
*** Concentrated solar power via solar-thermal steam turbine with dry cooling system

only the gross land area demand is considered in the present section (for details of the underlying assumptions and calculations, see Annex Section 7.3).

The area-specific fuel yields of PtL from photovoltaic and wind power are listed in **Table 7** in comparison to several production pathways based on biomass feedstock. **Table 7** also shows a translation of the area-specific fuel yields into the achievable air mileage based on fuel yield per hectare and year. An illustration of area-specific yields of several PtL pathway configurations in comparison with biofuels is presented in **Figure 8**.

As can be clearly seen from **Table 7** and **Figure 8**, the area-specific fuel yield of PtL is generally high and superior to the yields achieved with biofuels. Importantly, this comparison is drawn based on the gross area demand, with PV and especially wind power having substantially lower land coverage than agricultural biomass production (land coverage near 100 %). This means that especially in case of wind power, the occupied land can still be used for other purposes.

It is also important to acknowledge that it is not only the amount of land area required for production that has to be considered, it is also the type of land. Renewable power generation in principle does not depend on arable land, with desert regions, for example, offering highly suitable conditions for photovoltaic or solar-thermal power generation. Consequently, the risk of competition between energy and food production is strongly reduced.

Greenhouse gas emissions

The need to reduce the sector's greenhouse gas (GHG) emissions is the main driver behind the increasing interest of the aviation industry in alternative fuels. Consequently, the specific GHG emissions of alternative fuels on a lifecycle basis represent a crucial performance indicator of any type of alternative fuels and an essential metric for the comparison of different production pathways. The high potential of PtL jet fuel derived from renewable electricity and CO_2 becomes particularly evident when comparing its GHG balance (as described in Section 3.3) with that of other non-conventional (biogenic as well as fossil) jet fuel options (**Table 8**).

Table 7

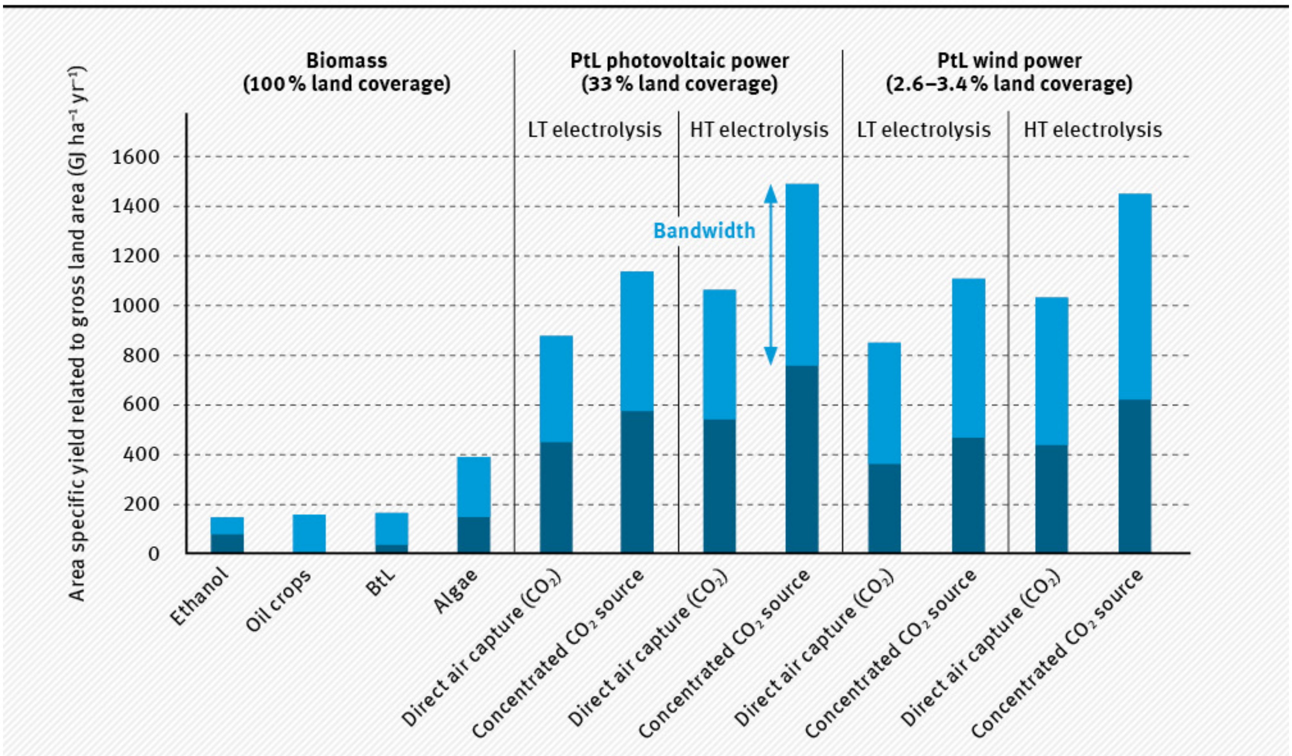
Area-specific yield and achievable air mileage related to gross area

Production pathway	Jet fuel yield (GJ ha^{-1} yr^{-1})	Achievable air mileage (km ha^{-1} yr^{-1})
Maize (AtJ)	84[1]	718
Sugar beet (AtJ)	149[2]	1271
Sugar cane (AtJ)	120[3]	1027
Jatropha oil (HEFA)	15–50[4]	124–425
Rapeseed oil (HEFA)	48[5]	407
Soybean oil (HEFA)	20[6]	167
Palm oil (HEFA)	162[7]	1379
Sunflower oil (HEFA)	31[8]	261
Algae oil (HEFA)	156–402[9]	1327–3422
Short rotation forestry (BtL)	47–171[10]	398–1456
PtL (photovoltaic electricity)	580–1070[11]	4950–9080
PtL (wind electricity)	470–1040[11]	4040–8860

(1) Corn yield in the USA: 9.45 t per ha and year (FAOSTAT 2016)
(2) Sugar beet yield in the EU: 71.65 t per ha and year (FAOSTAT 2016)
(3) Sugar cane yield in Brazil: 65.62 t per ha and year (UNICA 2013)
(4) Jatropha seed yield: 1.42 to 4.44 t; oil yield: 0.283 to 0.312 t per t of jatropha seed (IFEU 6/2008), (IFEU 12/2008); HEFA conversion yield according to (JEC 2014).
(5) Rapeseed yield in the EU (average 2010 to 2014 according to (FAOSTAT 2016)): 3.12 t per ha and year; oil yield: 0.424 t per t of rapeseed; HEFA conversion yield according to (JEC 2014).
(6) Soybean yield (weighted mix of Argentina, Brazil and USA based on FAO data for 2010 and 2011) used for life cycle analysis in (JEC 2014): 2.82 t per ha and year; oil yield: 0.193 t per t of soybean (FIDEOL 2014); HEFA conversion yield according to (JEC 2014).
(7) Yield fresh fruit bunches (FFB) in Malaysia: 20 t per ha and year (Hai 2004); oil yield (including kernel oil): 0.224 t per t of FFB (Coo et al 2011); HEFA conversion yield according to (JEC 2014).
(8) Sunflower seed yield in EU (average 2010 to 2014 according to (FAOSTAT 2016)): 1.92 t per ha and year; oil yield: 0.439 t per t of sunflower seed; HEFA conversion yield according to (JEC 2014).
(9) 25 to 64 t of algae biomass (dry substance) per ha and year derived from (Tredici 2012); oil content: 0.175 t per t of dry substance derived from (Lardon et al 2009); HEFA conversion yield according to (JEC 2014).
(10) Lower limit (poplar low limit from (KTBL 2016)): 6 t of dry substance per ha and year; upper limit (average eucalyptus yield in Brazil from (Oladosu and Sarlis 2010)): 22 t per ha and year; Biomass-to-liquid fuel efficiency BtL plant: 42 % (dena 2006)
(11) This study (LBST)

Figure 8

Comparison of gross area-specific yields of PtL fuels from photovoltaic and wind power and biofuels.



LT: low temperature; HT: high temperature; Algae: maximum yield depending on solar irradiation

Source: LBST

Table 8

'Well-to-wake' greenhouse gas emissions of various production pathways towards jet fuel, all data given in g_{CO_2eq}/MJ_{fuel}

Jet fuel pathway	GHG emissions without land-use change	GHG emissions including direct land-use change
Crude oil (reference)	87.5	–
Crude oil (ultra-low sulfur)	89.1	–
Oil sand (e.g. Canada)	103.4	–
Oil shale (in situ)	121.5	–
Natural gas (GtL)	101.0	–
Coal (CtL)	194.8	–
Switchgrass (BtL)	17.7	-2.0*
Soybean oil (HEFA)	37	97.8–564.2
Palm oil (HEFA)	30.1	39.8–698.0
Rapeseed oil (HEFA)	54.9	97.9
Jatropha oil (HEFA)	39.4	–
Algae oil (HEFA)	50.7	–
PtL (wind/PV in Germany)	~1	–
	11–28**	–

Source: This study (LBST & BHL) for PtL fuels; data for all other listed pathways from (Stratton 2010)
* Negative value because soil carbon from former vegetation lower compared to soil carbon for switchgrass
** Including construction of power plants and production facility (today)

The greenhouse gas emission impact of PtL fuels is mainly given by the emission intensity of the electricity supply and the CO_2 source. The emission intensity of the electric power input is crucial when a PtL facility is connected to a grid with a mix of fossil and renewable power plants. The origin of the CO_2 feedstock is important, since in-flight CO_2 emissions from fuel combustion need to be balanced to a large extent by prior CO_2 removal from the atmosphere to achieve substantial net greenhouse gas emission reductions relative to conventional jet fuel.

A controversially discussed source of CO_2 is flue gas captured from fossil power plants; apart from severe doubts about sustainability, this discussion usually ignores the fact that the current CO_2 market is saturated by more cost-efficient industrial CO_2 streams of both fossil (geologic sources, natural gas upgrading, hydrogen and ammonia production) and biogenic origin. Fermentation processes such as ethanol and biogas production show the lowest capture cost among industrial CO_2 sources, but their scalability is limited. Thus, short to medium-term implementations should be co-located close to existing low-cost CO_2 sources of biogenic origin, while CO_2 capture from air provides an important long-term scenario for very large scale sustainable fuel production, in particular at locations where no concentrated CO_2 sources of sufficient scale are available (UBA 2016), e.g. in rural regions with high solar irradiation. Generally, it has to be noted that a truly sustainable production is only possible if a renewable source for the feedstock CO_2 is exploited (UBA 2013; UBA 2016).

The specific greenhouse gas emissions for the PtL pathway have been evaluated in Section 3.3 under the assumption of renewable electricity input and CO_2 removal from the atmosphere either via biogenic CO_2 sources or air capture. The specific GHG emissions of PtL fuels compare favorably to specific GHG emission of other alternative fuels for aviation (**Table 8**). Importantly, this is not only true in comparison to unconventional fossil alternatives, such as gas-to-liquid (GtL) and coal-to-liquid (CtL), but also to various renewable options based on biomass feedstock.

In order to achieve a substantial reduction of GHG emissions caused by the aviation sector, an excellent *specific* GHG balance alone is not sufficient: The second performance indicator of key importance is the scalability of the production process, i.e. the production potential. In this respect, PtL fuels also offer a highly advantageous performance, as the global production potential for renewable electricity is huge and by far exceeds the total global energy demand. Notably, renewable electricity production does not depend on the availability of arable land, with e.g. deserts representing most suitable areas for electricity production through PV, CSP or onshore wind. Consequently, the risk of competition between energy and food production is intrinsically low in case of PtL. Therefore, the PtL production pathway offers a plausible opportunity to provide both robust sustainability and sufficient scalability to substitute a large fraction of the total volume of jet fuel consumed by aviation each year.

4.2 Economic competitiveness

The projected cost for the production of PtL fuels derived from renewable electricity is significantly higher than the current 2016 jet fuel price. Likewise the production cost of current biofuels does not compete with fossil fuels in terms of cost.

Steeply declining cost for renewable electricity generation from solar and wind energy are the main driver to reduce the projected production cost of PtL fuels (see **Figure 7**). Already today, onshore wind and PV power at excellent locations achieve electricity generation costs consistently around and even below 5 ct/kWh$_{el}$. Section 3.6 also illustrates the benefit from high energy conversion efficiency from electricity to fuels, e.g. through high-temperature electrolysis or improved CO_2 extraction. Bulk availability of low cost and sustainable CO_2 supply provides an opportunity for the economics of the first PtL plants.

An encouraging example of existing PtL plant is operated by Carbon Recycling International and HS Orka in Iceland. The plant has been running since 2012 and has expanded from 1.4 million L/yr to 5 million L/yr in 2015. It produces methanol from low-cost renewable energy in Iceland and benefits from high capacity factors and from a local high-purity CO_2 source of volcanic origin. Methanol itself is not a suitable fuel for aviation, but a valuable intermediate along the methanol pathway.

4.3 Complementary long-term options

Power-to-liquids offers a sustainable pathway for the large-scale production of jet fuel from H_2O, CO_2, and renewable energy (see Section 4.1). While PtL is the only plausible pathway to produce fuels from renewable electricity (wind, solar, geothermal or hydro power), there are further options for liquid fuel production by direct conversion of sunlight.

The **solar-thermochemical** fuel pathway aims at producing syngas – a hydrogen and carbon monoxide mixture – directly from concentrated solar radiation. The most advanced solar-thermochemical fuel production pathway is based on two-step redox cycles. Direct syngas production from concentrated solar radiation and subsequent synthesis of Fischer-Tropsch fuels has been demonstrated on laboratory scale within the EU project SOLAR-JET (TRL 3–4).

Furthermore there is a variety of **photo-electrochemical cell** concepts in the research pipeline that currently stand at TRL 2–5 (LBST et al 2015). These 'artificial leafs' convert solar energy in form of photons into chemical energy. Compared to the photovoltaic PtL pathway, photo-electrochemical cells omit the central electrolysis plant and some electric energy conversion losses, but require the supply of feedstock to and the collection of fuels from the full solar array area.

Thus, a number of promising energy conversion technologies exists, in particular for the direct conversion of solar energy into fuels. However, with regard to known technology, PtL is by far the most efficient and plausible option to convert large quantities of renewable energy from non-biogenic sources into synthetic jet fuel.

5 Conclusions and future perspectives

5.1 PtL for aviation – A story bright or bleak?

Strengths

The Power-to-Liquid pathway combines industrial process steps to produce sustainable jet fuel from large resources of renewable energy, such as solar and wind. Thus, it provides a credible perspective to produce large quantities of sustainable drop-in jet fuel. In case of renewable electricity and CO_2 provision, PtL fuels achieve very low levels of greenhouse gas emissions. Furthermore, if produced according to the technical specification for FT-derived synthetic fuels defined in ASTM D 7566, PtL fuels produced via the FT pathway are already approved for use in civil aviation. Compared to biofuels, PtL fuels show very low water demand and land use.

Opportunities
PtL fuels from solar and wind energy will be harvested from extensive areas. Thus, PtL fuels production can strengthen rural economies. More specifically, solar fuels are most efficiently produced from arid areas less suitable for biofuels production (Falter 2016). Shading from solar panels may reduce irradiation pressure on the topsoil, thus improving the situation of marginal lands and areas prone to desertification. Favorable wind energy resources are found both on barren and on arable land. Thus PtL fuel production can greatly enlarge the renewable feedstock basis for jet fuels and create business opportunities for regions with marginal suitability for biofuels production.

A very important environmental and social impact of PtL fuels is a considerable reduction of particulate matter emission from the combustion of synthetic hydrocarbon fuels compared to conventional fuels (Lobo 2011). The absence of sulfur and very low levels of aromatic content can significantly improve local air quality (Beyersdorf 2014). The positive health impact of ultra-clean synthetic fuels is well documented and of special importance in the aviation sector (Morita 2014) as exhaust aftertreatment is difficult to implement. In addition, contrail formation is expected to be reduced and, therefore, also the climate impact from radiative forcing caused by aircraft emissions in high altitude (Moore 2015). It has to be noted that these advantages are not PtL-specific, but rather properties of synthetic jet fuel in general.

Challenges/weaknesses
The main weakness of the PtL fuel path is the total cost of fuel production, which is directly linked to the capital cost and the energy conversion losses along the elaborate fuel production pathway. While the production cost will almost certainly continue to decline, e.g. due to cost reduction with renewable electricity generations and increasing efficiencies of production processes, PtL fuels will remain a fuel option with relatively high production cost on one hand and high rewards in terms of sustainability criteria on the other hand.

Like all drop-in substitutes for conventional jet fuels, PtL fuels can improve, but not eliminate local and high-altitude emission from fuel combustion. Zero emission is a key feature of electric motors, meriting research and demonstration into disruptive propulsion technologies in parallel with drop-in fuel developments.

Potential concerns/threats
The PtL pathway requires the utilization of low-carbon electricity and a sustainable CO_2 source in order to achieve low GHG emission. This could, e.g. be ensured by building utility-scale PtL facilities with a defined source of CO_2. In case a PtL facility is supplied with grid electricity and industrial CO_2 from the market, measures need to be taken to prevent a detrimental environmental performance and the lock-in of fossil power generation and fossil CO_2 sources for fuel synthesis.

Another potential concern for PtL is the required acceptance of extensive renewable power plants. The high area-specific yield is a profound advantage of PtL fuels compared to biofuels, thus the impact of PtL fuel production on land-use change is actually low compared to biofuels. Nevertheless, solar power plants and wind turbines do significantly alter the visual appearance of a landscape.

Another concern is associated with the use of hydro-electric power. The scalability of hydro-electric power generation is limited, and construction of hydro-electric dams changes river ecosystems and can have profound social impact on dam-effected population. Thus the utilization of hydropower for PtL production may be an opportunity for early projects but entails significant risks.

5.2 Considerations for the implementation of PtL-derived jet fuel

Demonstration projects
Economic and environmental impact of power-to-liquid fuels has been discussed in Section 3 and compared to other renewable fuels in Section 4. It was argued that the PtL is capable to efficiently utilize large renewable energy resources, such as solar energy and wind power for jet fuel production. This results in profound advantages in sustainability such as very low water consumption and high area specific yield. The main individual steps of the PtL process have already reached high technological readiness levels (Section 2). However, some technologies that would enable substantially improved process efficiencies – such as high-tempera-

ture electrolysis – or would allow for large-scale installations in remote, but highly suitable regions – such as CO_2 capture from air – have yet to be fully developed. Furthermore, the integration of the entire PtL process chain and the reverse water-gas-shift have to date only been realized at research level. In the near-term future, further demonstration projects at industrially relevant scale are required to develop individual process steps, to advance system integration and to pave the way for industrial implementation and commercialization of PtL production.

Activities supporting technology industrialization
The industrialization of key technologies, build-up of value chains and further improvement of PtL pathways is a major undertaking (UBA 2016). PtL developments can be flanked with the deployment and further scale-up of electrolyzers. The use of neat hydrogen and hydrogen-rich gases in bulk quantities is established practice in oil refining, the chemical and other industries. Power-to-hydrogen from renewable sources could be used already today, e.g. to

- improve the greenhouse gas emission balance of biofuel processes which require hydrogen, e.g. for hydrotreating;
- increase the yields of biofuel processes that are in excess of carbon, such as biomass digestion or gasification of biomass;
- substitute fossil hydrogen in crude-oil refineries.

These short-term actions can considerably improve the environmental performance of existing fuel production processes and prepare grounds for the industrialization of PtL pathways at the same time.

Support schemes
The gap between the cost of conventional and PtL fuels will decrease due to cost reduction of renewable electricity generation, improved energy conversion efficiency, and reduced investment as the technology evolves. However, without further support it is unlikely that any renewable fuel offering a high environmental performance will become cost-competitive in the near- to medium-term future. Fossil fuel production is most tightly constrained by emission targets (McGlade & Ekins 2014) yet to be enforced (rather than by resource scarcity); the production potential of biofuels is most tightly constrained by low energy conversion efficiency, the availability of suitable land, conserving natural habitats and ensuring food security. Thus, meeting sustainability targets with high-performing renewable fuels like PtL will likely require political measures. A supporting scheme tailored to renewable jet fuels should favor alternative fuels with large sustainability benefits in terms of greenhouse gas reduction potential, land requirement and water demand. In order to qualify PtL as renewable aviation fuel, a sustainable supply of renewable electricity, water and CO_2 needs to be guaranteed, which requires sustainability safeguards and a traceable monitoring scheme.

Logistics and siting
Further challenges for the introduction of PtL fuels relate to fuel logistics, technical approval, and sustainable feedstock provision. Many aspects of fuel logistics and technical approval are similar to known challenges for biofuel pathways which are, e.g. based on gasification of biomass or municipal waste. Conventional Fischer-Tropsch plants for synthetic jet fuel production from natural gas (GtL) or coal (CtL) are designed for very large capacity due to economies of scale. This results in significant financial risks and requires the feedstock availability at very large scale. In case of BtL fuel this challenge relates to the availability and logistics of hydrocarbon feedstock; in terms of PtL fuels this challenge relates to the availability of renewable electricity and CO_2 in the required quantity.

PtL can be produced at lowest cost at locations offering high renewable energy potentials, e.g. windy coastal regions or desert-like areas with high solar irradiation PtL intermediates, such as crude Fischer-Tropsch product or methanol, can be transported to central upgrading and conversion facilities to benefit from economies of scale.

Thanks to the high energy density of liquid hydrocarbons and existing transport infrastructures (tanker, pipeline, train, truck) PtL fuels offer an interesting long-term perspective for fossil oil exporting countries and territories with potentials of wind or solar power in excess of their own needs.

Blending at refinery
According to ASTM D7566, FT-SPK can be used in blends of up to 50% with conventional jet fuel. The ca-

pacity of early PtL fuel plants will likely be significantly smaller than conventional GtL and CtL facilities to avoid prohibitively high upfront investment cost. Thus it may be beneficial to "blend" the raw product of a PtL facility with the crude oil feed of existing refineries. This would require establishing or amending existing renewable fuel tracing schemes to qualify such feed stream as a renewable component of the final fuel product.

6 References

Airbus (2012):
Airbus, Global Market Forecast 2012–2031: Navigating the Future. Airbus S.A.S., 2012.

ANL et al (2012):
ANL; NREL; PNNL: Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne National Laboratory (ANL), Argonne, IL/USA; National Renewable Energy Laboratory (NREL), Golden, CO/USA; Pacific Northwest National Laboratory (PNNL), Richland, WA/USA. June 2012.

ATAG (2012):
A sustainable flightpath towards reducing emissions. Position paper presented by the Air Transport Action Group (ATAG) at the UNFCCC Climate Talks, Doha, 2012.

Beyersdorf (2014):
Beyersdorf, A. J.: Reductions in aircraft particulate emissions due to the use of Fischer-Tropsch fuels. Atmos. Chem. Phys. 14, 2014, Bd. 11., 2014.

Boeing (2013): Graham J.; Rahmes, T.; Kay, M.; Belières, J.-P.; Kinder, J.; Millet, S.; Ray, J.; Vannice, W.; Trela, J.: Impact of SPK Fuels and Fuel Blends on Non-Metallic Materials Used in Commercial Aircraft Fuel Systems. Submitted by The Boeing Company to FAA. 18.12.2013 (updated version).

Boeing (2013a): Current Market Outlook 2013–2032. Boeing Commercial Airplanes, 2013.

Coo et al (2011): Coo, Y.M.; Muhamad, H.; Hashim, Z.; Subramaniam, V.; Puah, C.W.; Tan, Y.; Determination of GHG Contributions By Subsystem In The Oil Palm Supply Chain Using The LCA Approach; Int J. Life Cycle Assess, 2011.

de Klerk (2011): de Klerk, A., University of Alberta, Chemicals and Material Engineering, Alberta, Canada: Fischer-Tropsch, Refining; Wiley-VCH, Weinheim, Germany; 2011; ISBN-978-3-527-32605-1.

dena (2006): Ludwig-Bölkow-Systemtechnik GmbH (LBST), Ottobrunn; Fichtner GmbH & Co. KG, Stuttgart; Rödl & Partner GbR, Nürnberg; NORD/LB, Hannover: Biomass to Liquid – BTL Realisierungsstudie; Zusammenfassung; by order of Deutsche Energie-Agentur GmbH (dena), unter Beteiligung des Verbandes der Automobilindustrie (VDA) sowie Adam Opel GmbH, Audi AG, BMW Group, DaimlerChrysler AG, Ford-Werke GmbH, MAN Nutzfahrzeuge, AG Volkswagen AG, BASF AG, Deutsche BP AG, TOTAL Deutschland GmbH, Lurgi AG, Choren Industries GmbH; Deutsch Energie-Agentur (DENA), Dezember 2006.

DLR et al (2012): Nitsch, J.; Pregger, Th.; Naegler, T.; Heide, D.; Luca de Tena, D.; Trieb, F.; Scholz, Y.; Nienhaus, K.; Deutsches Zentrum für Luft und Raumfahrt (DLR), Stuttgart; Gerhardt, N.; Sterner, M.; Trost, T.; von Oehsen, A.; Schwinn, R.; Pape, C.; Hahn, H.; Wickert, M.; Fraunhofer IWES, Kassel; Wenzel, B., IFNE, Teltow: Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global – "Leitstudie 2011"; BMU – FZK 03MAP146, 29. März 2012

DOE (2014): U.S. Department of Energy (DOE): The Water-Energy Nexus: Challenges and Opportunities. DOE Water-Energy Technology Team, June 2014.

European Advanced Biofuels Flight Path Initiative (2011):
2 Million tons per year: A performing biofuels supply chain for EU aviation. Technical paper presented by the European Advanced Biofuels Flight Path Initiative, 2011.

European Commission (2014): Horizon 2020 – Work Programme 2014–2015 – General Annexes: G. Technology readiness levels (TRL). Brussels, 23 July 2014.

Falter (2016): Falter F., Batteiger V., Sizmann A., Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production; Environ. Sci. Technol., 2016, 50 (1), pp 470–477

FAOSTAT (2016): Food and Agriculture Organization of the United Nations, Statistics Division: FAOSTAT; accessed 29 August 2016; http://faostat3.fao.org/browse/Q/QC/E

FIDEOL (2013): FEDIO: Lifecycle assessment of EU oilseed crushing and vegetable oil refining; May 2013.

Gießen (2015): Regierungspräsidium Gießen:
Windenergie; Energieportal Mittelhessen, Mai 2015; http://www.energieportalmittelhessen.de/energieuhrmittelhessen/mittelhessen/windenergie.html

Hai (2004): Teoh Cheng Hai, Eco Partners, Kuala Lumpur, Malaysia: Selling the green palm oil advantage; Oil Palm Industry Economic Journal (VOL 4(1)/2004).

Harp et al (2015): Harp, G. (Harp Process Chemistry Consulting); Tran, K.C. (CRI); Bergins, C. (MHPSE); Buddenberg, T. (MHPSE), Drach, I. (MHPS); Koytsoumpa, E.I. (MHPSE); Sigurbjornsson, O. (CRI): Application of Power to Methanol Technology to Integrated Steelworks for Profitability, Conversion Efficiency, and CO_2 Reduction; Proceedings 'International Metallurgical Trade Fair with Congress' Düsseldorf, 2015.

Hristova (2015): Hristova, D.: PPA clears way for 200-MW wind farm in Argentine Chubut; SeeNews.com, 23 November 2015.

IATA (2016): International Air Transport Association (IATA): Fuel price analysis; accessed 5 September 2016; http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx

ICAO (2011): International Civil Aviation Organization (ICAO): Assembly Resolution A37-19 on International Aviation and Climate Change and Next Steps. United Nations Framework Convention on Climate Change (UNFCCC), Thirty-fourth Session of the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA34), 6–16 June 2011, Bonn, Germany.

IEA (2012): International Energy Agency (IEA): World Energy Outlook 2012. Paris.

IEA (2015): International Energy Agency (IEA): World Energy Outlook – Special Report on Energy Climate and Change. Paris.

IFEU (12/2008): Rettenmaier, N.; Köppen, S.; Gärtner, Sv.; Reinhardt, G.; ifeu, Heidelberg: Screening Life Cycle Assessment of Hydrotreated Jatropha Oil; by order of Daimler AG, Stuttgart; 12 December 2008.

IFEU (6/2008): ifeu; CSMCRI; Uni Hohenheim: Basic data for Jatropha production and use – updated version; June 2008.

IFEU et al (2016): F. Bergk, K. Biemann, C. Heidt, W. Knörr, U. Lambrecht, T. Schmidt (IFEU); L. Ickert, M. Schmied (INFRAS); P. Schmidt, W. Weindorf (LBST): Klimaschutzbeitrag des Verkehrs bis 2050; UBA (ed.) Texte 56, Berlin, 2016.

IRENA (2015): International Renewable Energy Agency (IRENA): Renewable Energy in the Water, Energy & Food Nexus. January 2015.

IWES (2013): Bundesverband WindEnergie (BWE); Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES): Studie zum Potenzial der Windenergienutzung an Land, Mai 2011 (Februar 2013), Kassel.

JEC (2014): Joint Research Centre-EUCAR-CONCAWE collaboration (JEC): Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context; Version 4.a; Report EUR 26237 EN – April 2014; ISBN 978-92-79-33888-5 (pdf); http://iet.jrc.ec.europa.eu/about-jec/

JRC (2013): Joint Research Centre of the European Commission (JRC): Bioenergy and Water. Report EUR 26160.

Jungbluth (2007): N. Jungbluth, R. Frischknecht, M. Faist-Emmenegger, R. Steiner, M. Tuchschmid (ESU-services Ltd.): Life Cycle Assessment of BTL-fuel production: Life Cycle Impact Assessment and Interpretation. Uster, Switzerland, 30.07.2007.

Kennedy (2011): Kennedy, C.: Argentina's Largest Wind Farm in Patagonia Opens; OilPrice.com, 3 October 2011.

KTBL (2016): Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), Leibnitz-Institut für Agrartechnik in Potsdam-Bornim e.V. (ATB), Potsdam: Leistungs-Kostenrechnung Pflanzenbau; accessed 30.08.2016; http://daten.ktbl.de/dslkrpflanze/postHv.html#Ergebnis

Kuhn (2011): H. Kuhn, C. Falter, A. Sizmann, Renewable Energy Perspectives for Aviation. in: Proceedings of the 3rd CEAS Air&Space Conference and 21st AIDAA Congress, 2011, vol. 1259, pp. 1249–1259.

Lardon et al (2009): Lardon, L.; Géllas, A.; Sialve, B.; Steyer, J-Ph.; Bernard, O.; INRA: Life-Cycle Assessment of Biodiesel Production from Algae; Environmental Science & Technology, Vol. 43, No. 17, American Chemical Society, 27 July 2009; 6475-6481.

LBP (2015): Universität Stuttgart, Lehrstuhl für Bauphysik (LBP): Verbundprojekt sunfire – Herstellung von Kraftstoffen aus CO_2 und H_2O unter Nutzung regenerativer Energie: Arbeitspaket D Ökobilanz; by order of German BMBF, October 2015.

LBST (2016): Schmidt, P.; Zittel, W.; Weindorf, W.; Raksha, T. (Ludwig-Bölkow-Systemtechnik GmbH – LBST): Renewables in Transport 2050 – Empowering a sustainable mobility future with zero emission fuels from renewable electricity – Europe and Germany. Research Association for Combustion Engines (ed.), FVV-Report 1086/2016, Frankfurt a.M./Munich; accessed 06.09.2016, http://www.lbst.de/ressources/docs2016/FVV_H1086_Renewables-in-Transport-2050-Kraftstoffstudie_II.pdf

LBST et al (2015): Ludwig-Bölkow-Systemtechnik GmbH (LBST), Hinicio S.A.: Study on Hydrogen from Renewable Resources in the EU – Final Report; Munich/Brussels, July 2015.

Lobo (2011): Prem Lobo, P., Hagen, D.E., Whitefield, P.D. (Center of Excellence for Aerospace Particulate Emissions Reduction Research, Missouri University of Science and Technology, USA): Comparison of PM Emissions from a Commercial Jet Engine Burning Conventional, Biomass, and Fischer-Tropsch Fuels; Environmental Science & Technology, November 2011, 45, 10744–10749; dx.doi.org/10.1021/es201902e.

McGlade & Ekins (2014): McGlade, C., Ekins, P. (University College London (UCL), Institute for Sustainable Resources, London, UK): Unburnable oil: An examination of oil resource utilisation in a decarbonized energy system. Energy Policy 64 (2014) 102–112. http://dx.doi.org/10.1016/j.enpol.2013.09.042

Moore (2015): Moore, R. H.: Influence of Jet Fuel Composition on Aircraft Engine Emissions: A Synthesis of Aerosol Emissions Data from the NASA APEX, AAFEX, and ACCESS Missions. Energy & Fuels. 29(4), 2015, Bde. 2591-2600.

Morita (2014): Morita, H.: Global Health Impacts of Future Aviation Emissions under Alternative Control Scenarios. Environ. Sci. Technol. 48 (24), 2014, 14659.

Oladus & Sarlis (2010): Oladosu, G., ORNL – Environmental Sciences Division; Sarlis, C.E., The University of Tennessee – Knoxville: A Comparison of Empirical and Theoretical Eucalyptus Yields in Brazil; 2010.

Rutherford (2015): Rutherford, A.W. (Chair in Biochemistry of Solar Energy, Department of Life Sciences, Faculty of Natural Sciences, Imperial College London): Future Perspectives of Algae Fuels and Potential of Photosynthesis; 2nd Bauhaus Luftfahrt Symposium, Taufkirchen, Germany, 8 October 2015

Smolinka et al (2012): Smolinka, T. (Fraunhofer ISE); Garche, J. (FCBAT); Hebling, Ch. (Fraunhofer ISE); Ehret, O. (NOW GmbH): Overview on water electrolysis for hydrogen production and storage; presentation at the Symposium "Water electrolysis and hydrogen as part of the future Renewable Energy System", Copenhagen/Denmark, 10 May 2012.

Steiner (2010): Steiner, U. (Bayer Technology Services): Betrachtungen zur Energiebilanz und Wirtschaftlichkeit von Biokraftstoffen aus Algen; Workshop "Algenbiomasse", Darmstadt, Germany, 24 February 2010

Stephenson (2010): Stephenson, A., L.; Kazamia, E.; Dennis, J., S.; Howe, Chr., J.; Scott, St., A.; Smith, A., G.; University of Cambridge, UK: Life-Cycle Assessment of Potential Algae Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Reactors; Energy Fuels 2010, 24, 4062-4077.

Stratton (2010): Stratton, R.W.; Wong, H.M.; Hileman, J.I. (MIT): Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels; PARTNER (Partnership for Air Transportation Noise and Emissions Reduction), Project 28 report; June 2010.

Tredici (2012): Tredici, M., R., Dipartimento di Biotecnologie Agrarie Università degli Studi di Firenze, Italy: Energy balance of microalgae cultures in photobioreactors and ponds; EU Workshop Life Cycle Analysis of Algal Based Biofuels 9 February 2012.

UBA (2013): Purr, K. et al (German Environment Agency/Umweltbundesamt – UBA): Germany 2050 – A Greenhouse Gas-Neutral Country; UBA Background Paper // October 2013. Last accessed: 12.09.2016, https://www.umweltbundesamt.de/publikationen/germany-2050-a-greenhouse-gas-neutral-country

UBA (2014): German Environment Agency/Umweltbundesamt (UBA): Germany in 2050 – a greenhouse gas-neutral country. Climate Chance 07/2014, Dessau-Roßlau.

UBA (2016): Purr, K.; Osiek, D.; Lange, M.; Adlunger, K. (German Environment Agency/Umweltbundesamt – UBA): Integration of Power to Gas/Power to Liquids into the ongoing transformation process. – Position; Dessau-Roßlau, June 2016. Last accessed: 12.09.2016, https://www.umweltbundesamt.de/publikationen/integration-of-power-to-gas-power-to-liquids-into

UNFCCC (2015): United Nations (UN) Framework Convention on Climate Change (FCCC): ADOPTION OF THE PARIS AGREEMENT. Conference of the Parties Twenty-first session. FCCC/CP/2015/L.9, Paris, 12 December 2015.

UNICA (2013): Brazilian Sugar Cane Industry Association (UNICA): Final Report of the 2012/2013 Harvest, South-Central Region; 2013.

Windconcept (2013): Windconcept, Espelkamp: Flächenbedarf und Standortpacht; 2013 http://windconcept.de/wea_standort.html

7 Annex

7.1 Technology Readiness Levels (TRL)

TRL definition

Table 9

Definition of Technology Readiness Levels according to (European Commission 2014)

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 10

Current technology readiness level (TRL) of PtL key technologies

Technology	TRL (today)
Water electrolysis	
Alkaline electrolyser	9
Polymer-electrolyte membrane electrolyser (PEM)	8
High-temperature electrolyser cell (SOEC)	5
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
Absorption/desorption (TSA)	6
CO_2 conditioning (liquefaction and storage)	9

Technology	TRL (today)
Synthesis	
H_2 storage (stationary)	9
Fischer-Tropsch pathway	
Fischer-Tropsch synthesis	9
Reverse water gas shift (RWGS)	6
Hydrocracking, isomerization	9
Methanol pathway	
Methanol synthesis	9
DME synthesis	9
Olefin synthesis	9
Oligomerization	9
Hydrotreating	9
Complete PtL pathway	
considering CO_2 from concentrated sources; TRL determined by the weakest link in the production chain	
PtL from Fischer-Tropsch pathway with low-temperature electrolysis	6
PtL from Fischer-Tropsch pathway with high-temperature electrolysis	5
PtL from Methanol pathway with low-temperature electrolysis	8
PtL from Methanol pathway with high-temperature electrolysis	5

RWGS = reverse water gas shift; SOEC = solid oxide electrolysis cell; ASTM = American Society for Testing Materials (today: ASTM International) Source: LBST

7.2 Generic chemical reactions for PtL production

Kerosene consists of hydrocarbons with 6 to 16 carbon atoms per molecule. If a hydrocarbon molecule with 11 carbon atoms were used as an average for the whole fuel production process, the following reactions occur in case of the **methanol pathway:**

Water electrolysis:	$34\ H_2O$	→	$34\ H_2 + 17\ O_2$
Methanol syntheses:	$33\ H_2 + 11\ CO_2$	→	$11\ CH_3OH + 11\ H_2O$
DME syntheses:	$11\ CH_3OH$	→	$5.5\ CH_3\text{-}O\text{-}CH_3 + 5.5\ H_2O$
Olefin syntheses:	$5.5\ CH_3\text{-}O\text{-}CH_3$	→	$5.5\ (CH_2)_2 + 5.5\ H_2O$
Oligomerisation:	$5.5\ (CH_2)_2$	→	$C_{11}H_{22}$
Hydrogenation:	$C_{11}H_{22} + H_2$	→	$C_{11}H_{24}$
Total:	$\mathbf{12\ H_2O + 11\ CO_2}$	→	$\mathbf{C_{11}H_{24} + 17\ O_2}$

In case of the **Fisher-Tropsch pathway** the following reactions occur:

Water electrolysis:	$34\ H_2O$	→	$34\ H_2 + 17\ O_2$
Reverse water gas shift:	$11\ CO_2 + 11\ H_2$	→	$11\ CO + 11\ H_2O$
Fischer-Tropsch synthesis & upgrading:	$11\ CO + 23\ H_2$	→	$C_{11}H_{24} + 11\ H_2O$
Total:	$\mathbf{12\ H_2O + 11\ CO_2}$	→	$\mathbf{C_{11}H_{24} + 17\ O_2}$

7.3 Assumptions for the calculation of PtL land requirement

In case of **utility-scale photovoltaic** (PV) power plants a solar irradiation of 900 (Germany) and 1800 kWh (e.g. Northern Tunisia, Southern Spain) per ha and year has been assumed. The efficiency of the PV panel is 15 % and the performance ratio is 80 %. For a conservative estimation, the PV panel occupancy is equal to one third of the land area. 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. For wind power in the EU a rated power of 3 MW, a rotor diameter of 115 m and an equivalent full load period of 2071 hours per year as indicated in (IWES 2013) for Germany have been assumed (for comparison, (UBA 2013) found 2440 equivalent full load hours per year for average onshore wind power plants in German). For regions with high wind speeds (e.g. Argentina), a rotor diameter of 101 m and an equivalent full load period of 3747 hours per year (as e.g. observed at wind farm Parque eólico Rawson in Argentina) have been assumed.

To avoid shading about 210,000 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. 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 1.2 t to 2.4 % of the land are 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** with low temperature electrolysis combined with CO_2 from a concentrated source is applied for the lower limit which represents a location in central Europe. For the upper limit a PtL plant involving high temperature electrolysis and CO_2 from air 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 including electricity grid amounts to 45 % for low temperature electrolysis combined with CO_2 from biogas upgrading and about 42 % for high temperature electrolysis combined with CO_2 extracted from the air.

7.4 A brief look at algae yield assumptions

In case of algae derived fuels often unrealistically high biomass and fuel yields are stated (Steiner 2010), (Rutherford 2015). **Table 11** thus shows the calculation of the maximum yield of algae biomass according to (Tredici 2012). Higher yields at the given solar irradiation are not possible. ‘Low’ represents the irradiation in middle Europe, Northern USA or Southern Canada. ‘High’ represents the solar irradiation in Southern Spain or Northern Tunisia as indicated in (Tredici 2012).

Furthermore, there is a trade-off between high yield of algae biomass and high oil content (ANL et al 2012, p 76). High oil content leads to lower biomass yield, and vice versa. Both parameters are highly sensitive, influencing the overall production performance in terms of specific energy demand and costs.

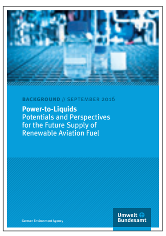
Table 11

Calculation of maximum real world yield of algae biomass

	Unit	Low	High
Total solar radiation (TSR) at sea level	MJ/(m² d)	9.0	17.4
	kWh/(m² yr)	913	1764
PAR (suitable radiation)	–	45 %	45 %
Maximum photosynthetic efficiency (PE) on PAR	–	27 %	27 %
Maximum (theoretical) PE on TSR (0.45 · 0.27 = 0.12)	–	12 %	12 %
Maximum PE under optimal conditions outdoors on TSR	–	5.0 %	5.0 %
Maximum PE under real conditions on TSR	–	2.5 %	2.5 %
Actual best average in industrial plants on TSR	–	1.5 %	2.0 %
Biomass yield	MJ/(m² d)	0.135	0.348
	g/(m² d)	7	17
	t_{DM}/(ha yr)	25	64

PE = photosynthetic efficiency, PAR = photosynthetically active radiation, t_{DM} = tonne dry matter

Source: LBST based on (Tredici 2012)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