Aviation Initiative for Renewable Energy in Germany e.V.

Sustainable Aviation Fuels

Status, Options, Necessary Actions

aireg Roadmap for the Deployment of Sustainable Aviation Fuels

Imprint

Sustainable Aviation Fuels. Status, Options, Necessary Actions
aireg Roadmap for the Deployment of Sustainable Aviation Fuels

aireg – Aviation Initiative for Renewable Energy in Germany e.V.
Bundesratufer 10
10555 Berlin
Phone: +49 (0) 178 184 30 41
E-Mail: kontakt@aireg.de
Website: www.aireg.de

COMPILED IN COORPORATION WITH

Hamburg University of Technology (TUHH)
Institute of Environmental Technology and Energy Economics (IUE)
Eißendorfer Str. 40
21073 Hamburg
www.tuhh.de/iue

Authors: Nils Bullerdiek, Ulf Neuling, Martin Kaltschmitt

Status: December 2020

PUBLISHER
aireg e. V.; Melanie Form, Member of the Board – Managing Director
(responsible in terms of press law)

Preamble

Dear readers,

the aviation industry is facing tremendous challenges in terms of climate and environmental protection. Especially Sustainable Aviation Fuels (SAF) have great potential to become a primary option for reducing air transport related greenhouse gas emissions. However, this requires joint efforts to develop and implement effective support measures embedded in long-term reliable framework conditions. Supporting the development of industrial production plants for SAF and striving for its economic competitiveness is essential.

SAF based on biogenic sources (e.g. plant-based oil and used oils, grease and municipal / industrial waste) are currently available in limited quantities only. Merely 0.1 % of the global kerosene demand is covered by such fuels. With the anticipated substantial global production increase in the coming two to three years, it is expected that the price for SAF could settle at a factor of about two compared to fossil kerosene. After recent extensive discussions with oil companies, leading aerospace companies and ATAG have indicated to ICAO that 100 % of the kerosene required worldwide in 2050 could be supplied by SAF.

Limited potential of biogenic resources will probably also limit the contribution of biogenic SAF in the long-term. Therefore, production processes must be promoted today that allow to produce SAF based on renewable energy, water and CO_2 via so called Power-to-Liquid (PtL) processes. This technology promises great climate gas emission savings but is still in an early development stage. Together with a market launch of sustainable biogenic SAF, PtL SAF must be developed and expanded into a large-scale, commercial, and cost-effective technology.

Aireg members developed proposals to foster semi-industrial demonstration plants as well as industrial production facilities in Germany, but also in foreign locations where conditions are more favorable to produce green hydrogen. Last but not least, the national hydrogen strategy of the German government has created the necessary funding framework. What is required now is the rapid implementation by the respective ministries.

My special thanks are due to the authors and all aireg members who contributed to the development of this roadmap. It presents an overall view of current and future SAF feedstock and technological options as well as obstacles and opportunities for the market introduction of SAF.

Siegfried Knecht
Chairman of the Board, aireg

Greeting

Dear readers,

sustainable energy sources based on renewable energy sources and feedstocks are cornerstones of the energy transition in Germany, Europe and worldwide. They are the requirements for the transformation in many industrial and economic sectors. Green hydrogen, therefore, plays a key role, as we need climate neutral alternatives to the present use of fossil fuels.

The German government has adopted, with the national hydrogen strategy, an action plan to improve the production and implementation of sustainable hydrogen along with its daughter products (Power-to-X), create new production chains for the German economy, build and expand essential transport infrastructure, focus research funding and facilitate international energy policy cooperation. This strategy must now be further brought to life.

Hydrogen technology and alternative energy sources are a fundamental part of the energy transition. Some areas of application, for example, air and sea transport, the worldwide existing fleets as well as selected industries with process related emissions with high energy requirements, will not be able to solely or at great expense, be supplied directly with electricity in the long term. Many routes for the mobile systems, particularly in aviation, in the national and allied defense and in the maritime sector cannot be implemented purely electrically. That is why current usage of fossil feedstock and energy sources must be quickly replaced by alternatives which are based on renewable power such as sustainable fuel produced by PtX processes.

As a member of the aireg advisory board, I support the dedicated work of the aireg members on their journey to a climate neutral aviation. I am, thereby, pleased over the courageous approaches taken to facilitate hydrogen powered and fully electrically driven aircraft. This roadmap is an essential guide for the path to this goal and an invitation to all stakeholders for a sustainable cooperation.

Norbert Barthle, MdB

Parliamentary State Secretary
at the Federal Minister for Economic Cooperation and Development

Content

Climate Protection in Aviation

Air Traffic Development

As global living standards continuously increased in recent years, there has been an equally noticeable rise in worldwide mobility levels. Supply chains have become increasingly globalized and currently often extend over multiple countries and continents. Thereby, aviation has become a backbone of a functioning and strongly connected economy, growing international trade, and intensified cultural exchange. Furthermore, global competition within the liberalized aviation markets lead to continuously decreasing ticket prices, which further boosted the demand for flight travel and air transport. Due to these and further factors, aviation has grown rapidly past and considerably more than any other mode of transport; this applies to the passengers as well as transported goods. The number of passengers between 1980 and 2019 has increased by a factor of approx. seven (Fig. 1).

Compared to this sector's considerable growth, however, the corresponding kerosene demand has risen less sharply. As the fuel prices significantly determine airline competitiveness, commercial airlines have a permanent incentive to constantly reduce the fuel requirements of their aircraft fleets.

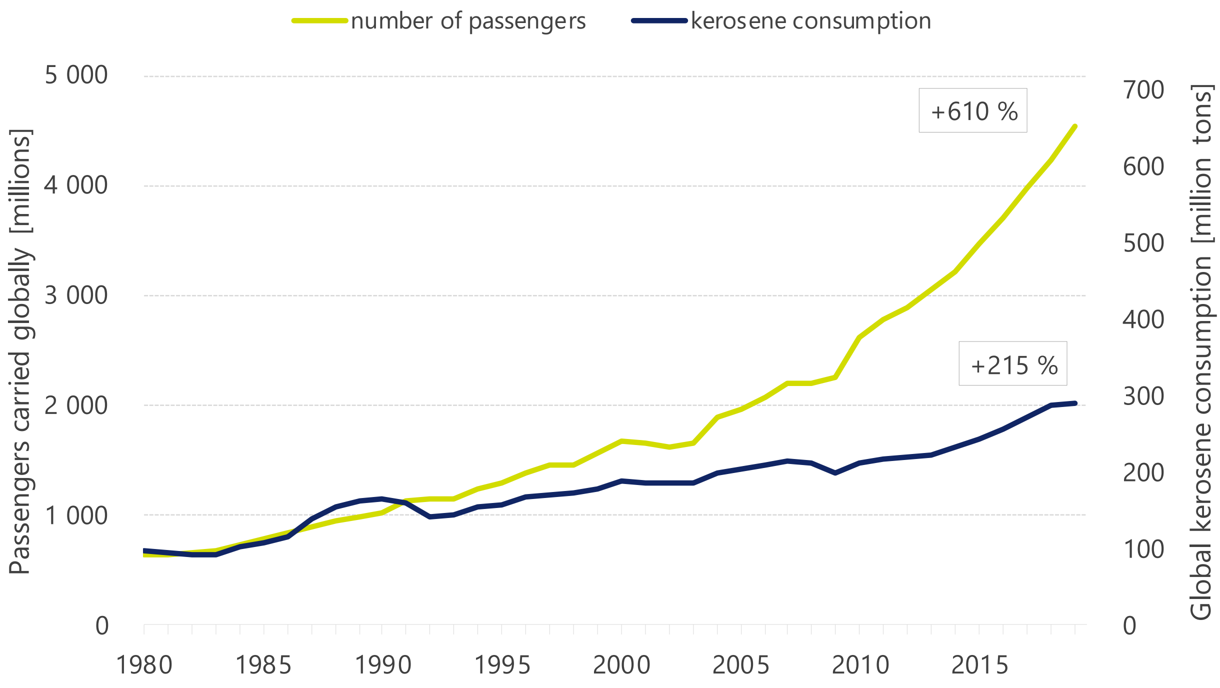


Fig. 1 **Air traffic development 1980 to 2019 (number of passengers and kerosene consumption)**
[IATA 2020b, 2020c; World Bank 2020; EIA 2020]

In the past, this was achieved mainly through technical and operational improvement, such as more fuel-efficient engines, lightweight options and materials in aircraft construction, optimized flight routes or higher seat occupancy rates. The average fuel consumption of an aircraft has been continuously reduced by such measures and the kerosene expenditure has been decoupled from the general growth of the aviation industry.

Despite the current significant efficiency gains, the fuel consumption in the commercial airline industry has nearly tripled since the early years of 1990. The reason for this is the relatively strong growth of the sector; the achieved fuel reductions were over-compensated by the growth related high additional kerosene demand.

The consequently permanent increase in air traffic also led to a sharp rise in the aviation-related greenhouse gas (GHG) emissions.

Because of the COVID-19 pandemic, the aviation industry has suffered a worldwide collapse since the beginning of 2020 (Fig. 2). The consequences of the COVID-19 pandemic will still, from today's perspective, have lingering effects, significantly affecting the short- and medium-term growth of the sector. Various factors that can hardly be quantified reliably – as the risk perception of governments or passengers, quarantine regulations or hygiene guidelines – determine whether or when air travel will achieve a pre-pandemic level.

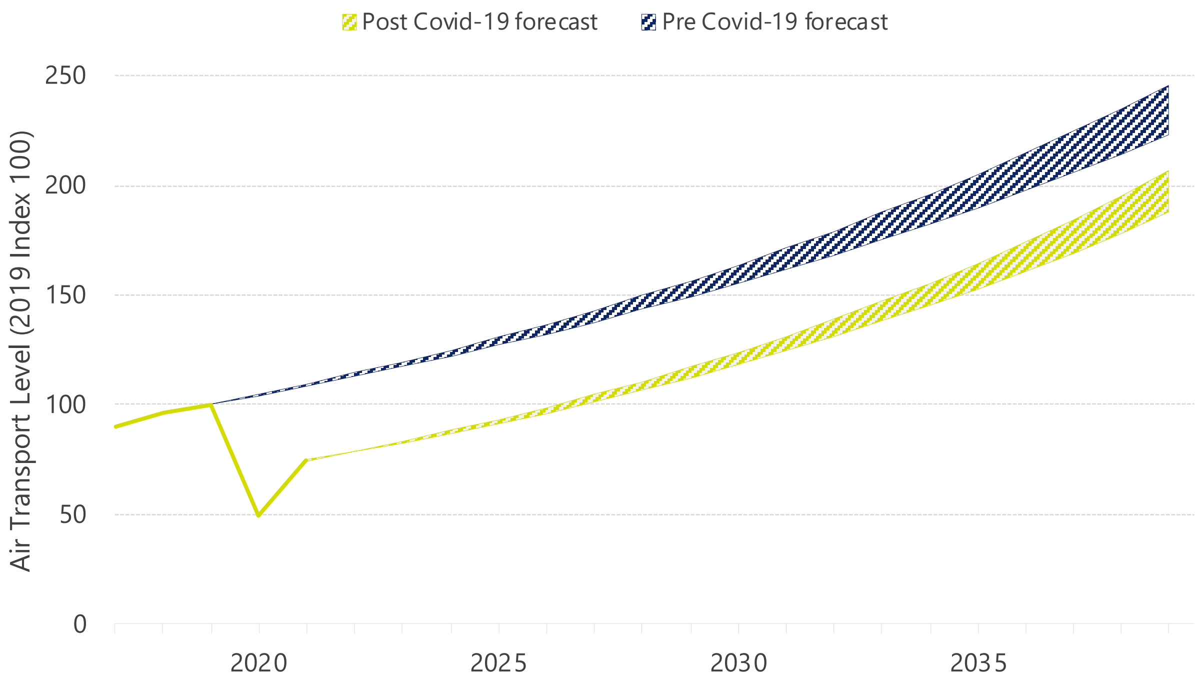


Fig. 2 **Air traffic projections 2021 to 2039**
[IATA 2020b, 2020a; ICAO 2018; Airbus 2019; Boeing 2019]

Particularly the number of business trips could subsequently decrease when companies decide to replace face-to-face meetings with video conferences [IEA 2020].

Even though the previous short- and medium-term effects of the COVID-19 pandemic on the aviation growth cannot yet be reliably determined, national and international aviation associations continue to assume a long-term increase in air traffic. The governing body of airlines (International Air Transport Association, IATA) predicts an annual 3.7 % air travel growth between 2019 and 2039, this correlates to a duplication in the two coming decades (Fig. 2) along with the corresponding increase of energy-related climate gas emissions.

Various options for reducing fuel consumption and therefore GHG emissions from aircraft-specifically economically implementable technical measures- were already successfully exhausted in the past. Further marginal energy- and thus climate gas reduction efficiency gains can presently only be achieved with a respectively high expenditure of cost and time. Even if airlines are further pressured by the pandemic to minimize their operative costs and modernize current fleets (out-phasing older aircraft), a continued global increase in air travel leads to a further rise in aviation-related GHG emissions unless adequate counter measures are implemented in the sector.

A climate and environmentally friendly design of air transport is therefore imperative if the services of a modernized aviation are to continue to be available in a globalized society.

International Climate Protection Strategy

The need to reduce the climate impact of air travel, has already been recognized by the aviation industry. International aviation industry stakeholders adopted a long-term supranational strategy in 2009, through which the CO_2-emissions of the global commercial air traffic shall be reduced to 50 % by 2050 compared to 2005 levels. This strategy, also called the 4-Pillar-Strategy, contains technical, operational and infrastructural measures as well as a market-based instrument to compensate for aviation emissions [aireg 2012; IATA 2018]:

- **Technical Measures.** Technical measures for example include the development of fuel-efficient engines, usage of lightweight materials or aerodynamically improved wings. This category also contains the development of innovative aircraft technologies and implementation of sustainable aviation fuels.
- **Operational Measures.** This set of measures comprises efficiency advancement in aircraft operations, e.g. through greater (seat) load factors, improved aircraft sizes, fuel-saving instrument approach procedures or optimized ground operational processes.
- **Infrastructural Measures.** These measures contain improvements to aviation infrastructure, such as the development of demand-based airport concepts without (if avoidable) delay patterns on the ground or

holding patterns in the air as well as modernized air traffic management systems or advanced aerospace concepts.

- **Emissions Compensation (CORSIA).** This category primarily includes the market-based offsetting scheme "CORSIA". This instrument is intended to offset CO_2 emissions produced by international air transport through CO_2 savings realized outside the actual aviation sector (i.e. out-of-sector measures). Furthermore, this should enable neutral CO_2 growth in the international aviation sector from 2021 onwards.

As there is no "silver bullet" to further de-fossilize the aviation sector, all measures of this 4-pillar strategy should be progressively executed if possible. There are, however, specific individual or multiple measures which clearly indicate limitations and as such a priori restricted potential, meaning that they can only partially contribute to further reduce emissions in global air transport in a foreseeable period. The development of fundamental technical improvements often takes years and require high investments only to result in relatively low efficiency gains. Additionally, the rate at which aircraft fleets are modernized is rather low as aircraft have a (very) long life cycle, typically 20 to 30 years. Also, the implementation of specific technical improvements and retrofits require long time periods to become completely implemented in aircraft fleets. The (incremental) technical improvements, henceforth, only perform a timely delayed contribution to climate protection in commercial aviation and to a limited extent.

Operational and infrastructural measures often also require high development costs with comparatively low emission savings. Even though different approaches – some of which being extremely innovative – are pursued, their overall contribution to reduce GHG emissions is considered rather restricted. In conclusion, operational and infrastructural measures, within the frameworks of the 4-pillar strategy, only contribute to a limited extent in reducing aviation related GHG emission reductions.

Commercial airlines can offset climate gas emissions that exceed a defined limit within the scope of CORSIA. This limit originally corresponded with the average emission levels of 2019 and 2020, however, due to the effects of the COVID-19 pandemic, this limit now solely refers to the year 2019 [ICAO 2020].

These GHG emissions, within the framework of this offset instrument, are compensated through a purchase of certificates (CORISA offsets). These offsets are certified GHG savings from climate protection programs outside of the aviation industry. With the goal to enable such emission savings outside of the aviation industry at lower costs compared to intra-sectoral measures, CORISA shall serve as a cost-effective instrument to compensate growth-related CO_2 emissions. However, the aviation sector itself will not become climate friendly, as this would require inter-sectoral measures to reduce GHG emissions. Additionally, if GHG emissions can be reduced and cost-efficient offsets are possible in large quantities outside of the actual aviation sector, there are no further (financial) incentives to reduce climate gas emissions within the sector and consequently in the commercial air transport industry (e.g. by increasing efficiency or the use of sustainable aviation fuels).

Moreover, CORSIA only addresses international aviation and exempts national air transport, also for states with a high share in domestic air traffic (e.g. USA, China, Russia, India). If GHG reduction efforts are undertaken globally and if the climate protection targets, which have been adopted under binding international law, are to be adhered to, it will be necessary to continue to foster intra-sectoral options to reduce GHG emissions in aviation.

Technology Innovation and Sustainable Aviation Fuels

Technological, operational, and infrastructural options as well as CORSIA will most likely not be sufficient for a long-term climate friendly aviation sector. For this reason, technology innovations and particularly sustainable aviation fuels (SAF) are two additional fundamental components of the 4-pillar strategy, with which a large part of the GHG reduction is to be achieved in the long-term.

Technology Innovation

Currently two main (innovative) aviation technologies are being pursued: hydrogen and battery-electric powered aircraft. Both have a significant potential to reduce air traffic related GHG emissions in the future, especially non-CO_2 effects[1]. However, both options require intensive further work of research and development before they can be introduced as mature and commercially viable aircraft technologies. From today's perspective this will take more than a decade.

Moreover, they require the implementation of a separate fuel / energy supply infrastructure (e.g. liquid hydrogen) as well as the development for corresponding production and storage infrastructure to produce hydrogen or electrical energy from renewable energies on a large-scale.

Hydrogen Aircraft. The use of hydrogen in aircraft, especially if it is intended to exceed the deployment in auxiliary turbines or on-board power supply, necessitate more advanced technological, infrastructural, and operational developments which go beyond today's standard of technology. To successfully incorporate liquid hydrogen in a commercial aircraft, essential components such as fuel tanks and crucial parts of the propulsion system must be completely redesigned.

---

[1] In addition to combustion-related GHG emissions, the use of kerosene results in so-called non-CO_2 effects, e.g. particle emissions or water vapor, which lead to cloud formation and are also climate-relevant. According to current knowledge, only about one third of the climate impact of aviation is due to CO_2 emissions, while two thirds are due to non-CO_2 effects (e.g. contrails).

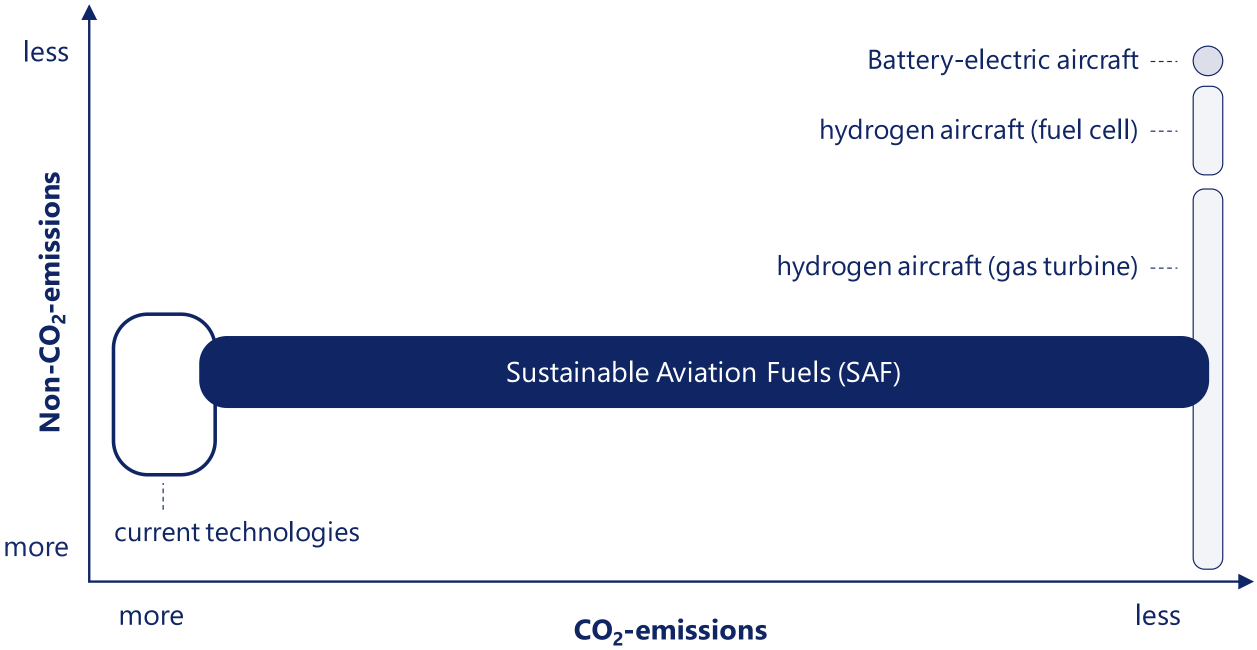


Fig. 3 **Emission comparison of different technologies**
(Based on Thomson et al. 2020b)

There are two main approaches being pursued for the propulsion of hydrogen aircraft: the use of hydrogen in modified gas turbines and in fuel cells. The incorporation in gas turbines potentially requires less developmental work compared to the use in fuel cells, possibly enabling a timely use of hydrogen in aviation. Nonetheless, the utilization of hydrogen in fuel cells could further reduce the overall GHG emissions (Fig. 3). However, this requires a further development of fuel cell technology.

In addition to propulsion difficulties, the storage of hydrogen on board the aircraft presently poses a significant challenge. Even though hydrogen is lighter than conventional fossil fuel (per unit of energy), it requires a significantly larger storage volume. In addition to propulsion difficulties, the storage of hydrogen on board the aircraft presently poses a significant challenge. Even though hydrogen is lighter than conventional fossil fuel, in terms of per unit of energy, it requires a significantly larger storage volume. Storing hydrogen on board the aircraft, therefore, entails greater tank systems integrated in the aircraft and partially requires a completely new aircraft and wing construction. Besides such an integration of larger tank capacity on board the aircraft, the tank system itself must also be adjusted. While conventional kerosene can be stored in a liquid state during the entire flight, hydrogen, on the other hand, requires a more complex storage, as hydrogen is in a gaseous form at ambient conditions. Up to this point, cryogenic storage options have been predominantly considered for aviation i.e. hydrogen storage at very low temperatures of at least approx. -253 °C. This type of extremely cold storage requires modern cryogenic tank systems and insulation options.

Parallel to aircraft developments, the construction of a corresponding hydrogen infrastructure is required to facilitate the availability of hydrogen supply to aerodromes and within aerodromes. This energy supply infrastructure must be constructed and operated parallel to the existing kerosene infrastructure. For hydrogen to be implemented as effectively as possible, such supply infrastructures should be available at the central hubs in the international route network (i.e. at the larger airports). If hydrogen availability would be limited to individual countries and airports in the long term, airlines would severely be restricted in the use of their hydrogen fleet. Therefore, efforts must be made to facilitate an efficient transition from the current system to the future supply infrastructure.

Furthermore, sustainable production and sufficient supply of hydrogen is necessary for it to reduce climate gas emissions from aviation. This specifically requires an abundant supply of renewable energy (e.g. wind and solar power). The path for the expansion of hydrogen is currently paved out on a political and regulatory level in Germany and Europe. In other words. The availability and supply of (sustainable) hydrogen will, particularly in the early stages of large-scale use, most likely be limited and the many areas in which this fuel is applicable, will face a competitive situation. It must therefore be ensured, that hydrogen is also available for aviation if a large-scale use is intended.

Battery-Electric Aircraft. The present propulsion components and energy sources of battery-electric aircraft i.e. the gas turbine and kerosene, are to be completely replaced by an electric motor with a battery as energy storage. The advantage of this propulsion and energy storage configuration is an overall high performance efficiency of the propulsion components, which is twice as high as that of conventional aircraft engines [DLR und BDLI 2020, 27].

Battery-electric aircraft, similarly to hydrogen aircraft, still face multiple technical challenges in aviation. Especially batteries with a sufficiently high energy density and proportionately low weight play a key role in achieving the use of fully electric aircraft. Today's current batteries (still) have a considerably low energy density; compared to conventional (fossil) fuel this is lower by a factor of 25. It is, thereby extremely difficult to carry abundant energy on board to fuel the respective flight, henceforth strongly reducing the possible range at which the aircraft can be operated. The range of application of electric aircraft is, from today's perspective, primarily limited to short-haul flights or to areas of application in the urban air mobility [DLR und BDLI 2020].

Furthermore, the use of battery-electric aircraft requires the appropriate airport infrastructure for charging or rapid replacement of batteries. This type of infrastructure, comparable to that of hydrogen, should at the very least be available at the central hubs in the respective route network of the individual airlines so that electric aircraft be used as efficiently and comprehensively as possible.

Depending on how the utilization of hydrogen aircraft evolves, the infrastructure for battery-electric aircraft would – in a transition period at the very least – coexist with hydrogen and the current kerosene infrastructure. Such a ternary fuel infrastructure, in other words the co-existence of three energy supply infrastructures, would substantially differentiate itself from today's aviation fuel infrastructure which is consistently accessible on a worldwide scale.

For this technology to reduce climate gas emissions, the energy – as with hydrogen – must be generated from renewable sources such as wind or solar power. The required supply of renewable electrical energy is potentially subject to strong competition, especially in market ramp-up phases, and may pose challenges in the further development of conversion plants (e.g. wind power plants).

Conclusion Technology Innovation

Technological innovations provide the opportunity to massively reduce climate gas emissions in aviation. This, however, requires years of intensive development work before experience with this technology is made and the first machines can be deployed in the first commercial flight routes (e.g. short-haul routes). Furthermore, it will take years to decades before these new technologies can sufficiently be fused with the current aircraft fleets, subsequently reducing the climate gases in a magnitude that is noticeable. Reason for this is the aircraft´s long technical utilization period and low modernization cycle of the fleets along with a continued use of the aircraft.

Even though aircraft powered by alternative energy sources are, from today's perspective, essential for a climate friendly aviation, the technology, due to the mentioned limitations, will not be available on a -scale in the short and medium term. With a continued rise of air traffic after overcoming the Covid-19 pandemic and hence an increase of GHG emissions, options must be pursued parallel to the development and availability of these new technologies, which are ("immediately") available in the near-term and that facilitate a notable reduction of GHG emissions within currently existing aircraft fleets.

Sustainable Aviation Fuels

Sustainable aviation fuels (SAF), compared to innovative technologies, can be made available and be scaled up in the nearer future. They can be used as so-called "drop-in" fuels in existing aircraft and the existing fuel supply infrastructure. The achievable climate GHG reductions by SAF therefore neither depend on fleet modernization rates nor comparable factors. SAF are consequently necessary for a timely and significant reduction of GHG emissions in aviation. A large-scale SAF market-ramp-up in the near future is only viable based on sustainable biogenic SAF, while electricity-based SAF are especially necessary in the long-term [WEF 2020; CST 2020]. It is crucial that only sustainable feedstocks are used for SAF production.

Overall, the potential of sustainable fuel options in the aviation industry has so far remained largely untapped. All biogenic and non-biogenic sustainable feedstocks must be utilized and promoted so that sustainable aviation fuels are available on a large-scale for air transport. This calls for an effective market-scale-up and an encompassing strategy.

Sustainable aviation fuels are essential for an opportune and momentous reduction in aviation GHG emissions. An effective market-ramp-up for biogenic and non- biogenic sustainable fuels requires a target-oriented and consistent strategy.

Sustainable aviation fuels are essential for a timely reduction of aviation-related GHG reductions in significant dimensions.

An effective market ramp-up of biogenic and non-biogenic sustainable aviation fuels requires a target-oriented and consistent strategy.

Sustainable Aviation Fuels

Today the aviation industry exclusively uses fossil kerosene, which is derived crude oil. This fuel has favorable properties for the use in aircraft. In contrast to diesel fuels, it only freezes at temperatures below -47 °C. Additionally, compared to gasoline, it is less volatile and flammable making it safer to handle. These are some of the reasons why kerosene has become the dominating fuel of the civil aviation industry and practically has a worldwide monopoly position.

Different types of kerosene can be used depending on the application and the corresponding requirements. For civil aviation there are two main types of kerosene used, the jet fuel JET A and JET A-1. The main difference between these grades is the freezing point. JET A, which is mainly used in North America must have a freezing point of at least -40 °C, whilst for JET A-1 this is at least -47 °C.

.

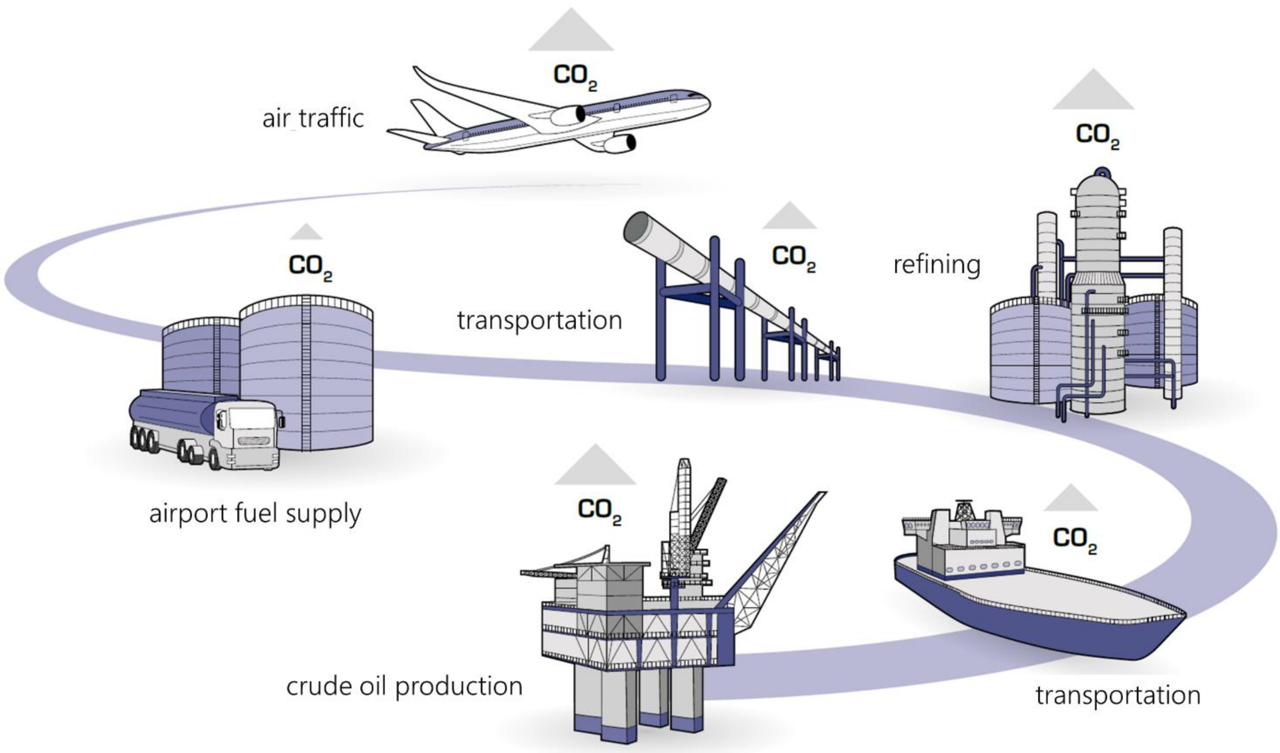


Fig. 4 **CO_2-life cycle of fossil aviation fuels**
(aireg 2012)

Sustainable Aviation Fuels (SAF)

The currently dominating fossil aviation fuels are not the only approved fuel options for the civil aviation industry. Also non-fossil fuels that can be produced based on different renewable biogenic and non-biogenic feedstocks can be used. These fuels which are also referred to as renewable or alternative jet fuels are presently mainly subsumed as "Sustainable Aviation Fuel" (SAF). From a climate perspective, the advantage of their use is that they produce less GHG emissions compared to fossil aviation fuels.

The generic term “SAF” covers a broad range of combinations of non-fossil feedstocks and chemical, biochemical and /or thermochemical conversion processes, that are used for producing aviation fuel. Furthermore, they can also be sued to produce other fuels (e.g. diesel) and/or other products (e.g. chemicals) in a coupled production. The types of sustainable aviation fuels can be classified into three categories.

- **Biogenic SAF.** The term, biogenic or biomass based SAF (biokerosene), covers a broad scope of different SAF options that are produced from oil, fat, starch, or sugar containing biomass and/or lignocellulosic (woody and semi-woody) biomass. This includes for example plant oils, algae, specific components of energy plants, organic municipal- and industrial-waste, or agricultural and forestry residues.
- **Electricity-based SAF.** The term electricity-based SAF or Power-to-Liquid (PtL) SAF defines sustainable aviation fuels which are not produced based on biomass but solely based on electricity from renewable sources, water, and CO_2.
- **Hybrid SAF.** Hybrid SAF (also called PBtL SAF) origin from hybrid production processes or combined biomass and electricity-based processes. Other than pure electricity-based approaches, water, CO_2, and electricity are not the only possible input materials. Besides electricity, a further carbon source (e.g. bio methane), which already contains a part of the energy of the final aviation fuel, is used for production.

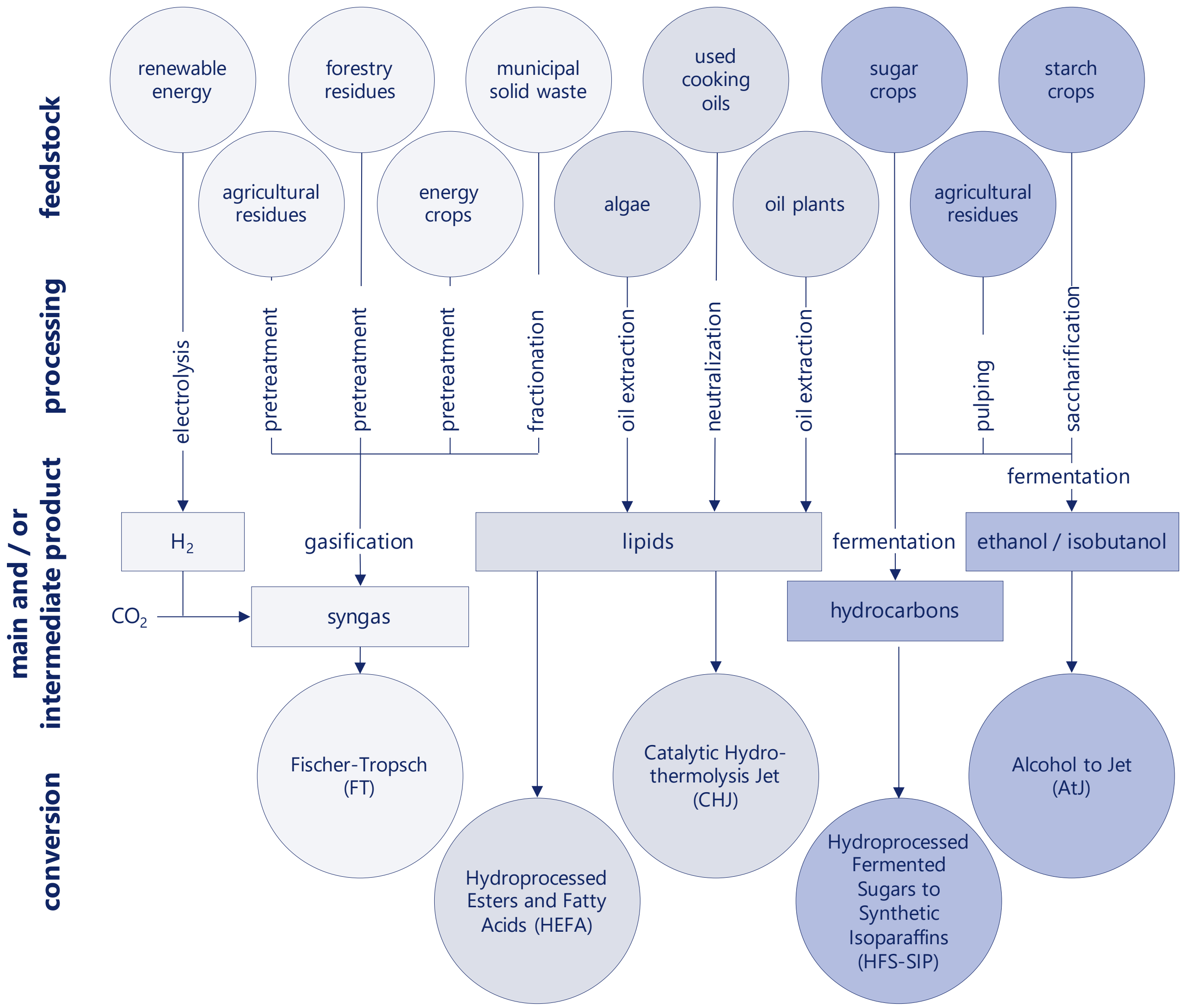


Fig. 5 **General overview of SAF production pathways**
(Based on Thomson et al. 2020a)

Figure 5 shows a general overview of the essential SAF production pathways, possible combinations of feedstocks and conversion processes.

Depending on the biomass used, various pretreatment steps are necessary to produce biogenic SAF to further process the feedstocks into a liquid fuel that conforms to aviation standards. The feedstock, typically after a pretreatment is converted, via a first conversion step, to an intermediate product such as alcohol (e.g. isobutanol or ethanol), synthesis gas, so-called "bio-crude oil" or other hydrocarbon mixtures. These intermediate products are then converted via a second conversion step, into a bio kerosene.

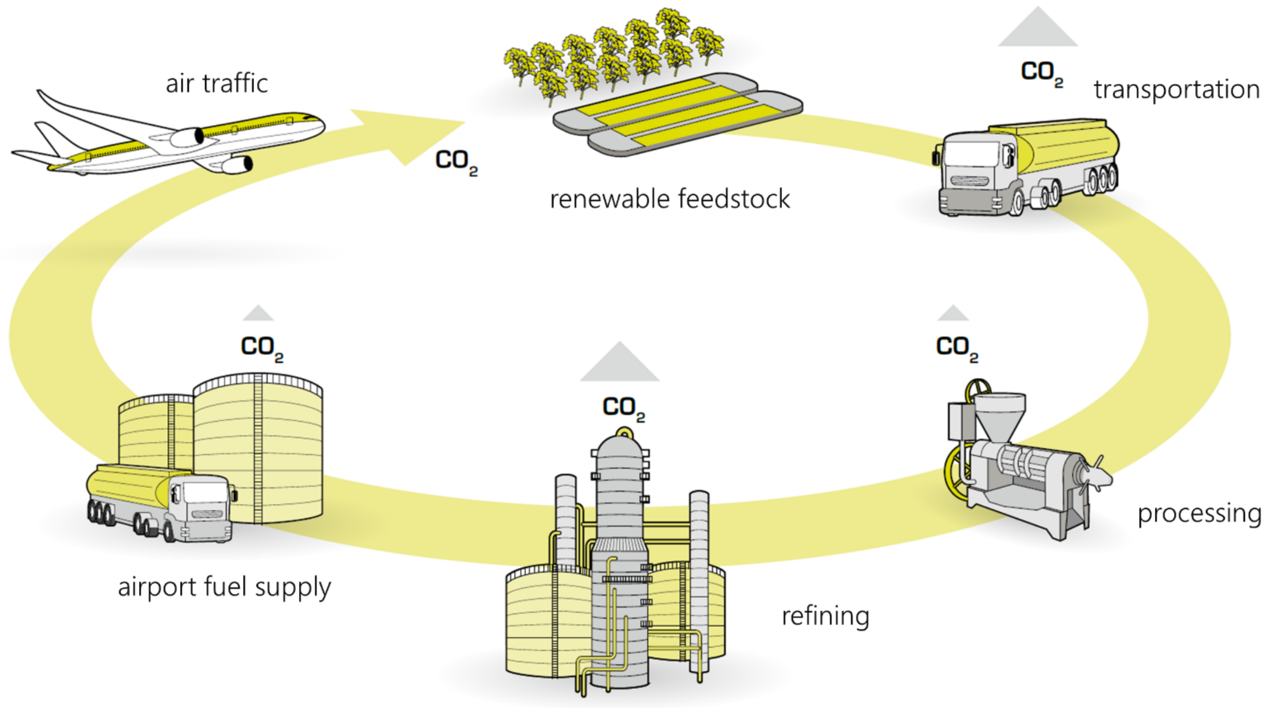


Fig. 6 **CO_2-life cycle of biogenic aviation fuels**
(aireg 2012)

The production of PtL SAF is exclusively based on water, CO_2 and electricity. In this process, water is first converted into hydrogen via an electrolysis process by using electrical energy (from renewable energy sources), which is then converted together with CO_2 into a synthesis gas (i.e. a gas mixture of carbon monoxide (CO) and hydrogen (H_2).

Prerequisites for the use of SAF

There are specific requirements for aviation fuels. They need to have a high energy density, good combustion properties and a variety of other (safety) criteria (e.g. performance at low temperatures). Furthermore, they must be simple to handle (i.e. easy transport, storage and/or pump) as they need to be available globally within a uniform quality.

For this reason, also sustainable aviation fuel options must be specifically approved for aviation. This approval is conducted by the international standardization organization ASTM International. Once a SAF option has successfully passed the appropriate approval procedures, it is added to the so-called ASTM D7566 specification (for Jet A-1 with synthetic hydrocarbon contents) or ASTM D1655. The approved SAF are then regularly adopted in the European DEF Stan 91-091 specification.

Furthermore, aviation fuel can only be used in commercial aviation if it meets all the requirements of the ASTM D1655 specifications. The properties prescribed therein are not necessarily fulfilled by (pure) sustainable aviation fuels, even if they have been produced in accordance with ASTM D7566. Prior to their use in aviation, they must therefore be blended with conventional or standard-compliant aviation fuel in such a way that they safely meet the requirements of ASTM D1655 at all times. For this purpose, certain blending limits are specified for various SAF options.

The maximum blending limit has so far been 50 % by volume. In practice, however, the maximum achievable blending ratio up to which a mixture still fulfils all the properties of ASTM D1655 also depends on the properties of the fossil blending component. If this has "unfavorable" properties, the maximum permissible blending limit may not be attainable. On the contrary, if the fossil components display "favorable" properties, higher blending ratios than the actual specified blending limits would be achievable, which still safely meet the requirements of ASTM D1655.

After the pure SAF component has been blended with ASTM D1655 compliant aviation fuel according to specifications, it can then be used in all existing commercial aircraft as well the existing fuel supply infrastructure (drop-in characteristic).

Aircraft, engine and fuel manufacturers are currently also working on the approval of SAF options which do not require a blended with conventional aviation fuel but can hence be used at 100 %. At present, these SAF options may require specific modifications of aircraft components (including sealings of the fuel system). As these are, per se not drop-in capable, they are thus also referred to as near drop-in fuels.

Tab. 1 Overview of approved SAF options (as of November 2020) according to ASTM D7566 and ASTM D1655)

ASTM	Annex	Approval	Process	Blending Limit	Possible Feedstock
D7566	1	2009	FT-SPK	50 Vol.-%	fats/oils (e.g. plant-based oils, used cooking oil)
D7566	2	2011	HEFA-SPK	50 Vol.-%	fats/oils (e.g. plant-based oils, used cooking oil)
D7566	3	2014	HFS-SIP	10 Vol.-%	sugar, starch, lignocellulose
D7566	4	2015	FT-SPK/A	50 Vol.-%	fats/oils (e.g. plant-based oils, used cooking oil)
D7566	5	2016	ATJ-SPK	50 Vol.-%	sugar, starch, lignocellulose
D7566	6	2020	CH-SK	50 Vol.-%	fats/oils (e.g. plant-based oils, used cooking oil)
D7566	7	2020	HC-HEFA-SPK	10 Vol.-%	fats/oils (algae oil)
D1655	1	2018	Co-Processing	5 Vol.-%	fats/oils (e.g. plant-based oils, used cooking oil)
D1655	1	2020	Co-Processing	5 Vol.-%	FT-biocrude (primarily feedstocks like FT-SPK, FT-SPK/A)

ATJ-SPK (Alcohol to Jet Synthetic Paraffinic Kerosene), **BtL** (Biomass-to-Liquid), **CH-SK** (Catalytic Hydrothermolysis Synthesized Kerosene), **FT** (Fischer-Tropsch), **HC** (Hydrocarbons), **HEFA** (Hydroprocessed Esters and Fatty Acids), **HFS-SIP** (Hydroprocessed Fermented Sugars to Synthetic Isoparaffins), **PtL** (Power-to-Liquid), **SPK** (Synthetic Paraffinic Kerosene), **SPK/A** (Synthetic Paraffinic Kerosene with Aromatics)

SAF Production Pathways

According to ASTM D7566, seven pathways have been approved for SAF production. The so-called Co-Processing presents a further option according to ASTM D1655, to use plant oils and animal fats in the production of SAF. Additional production pathways are currently under ASTM approval. According to their date of approval, Table 1 presents the currently approved SAF production pathways.

ASTM D7566 Annex 1 – FT-SPK

Process Description. Through the Fischer-Tropsch (FT) process, a synthesis gas of hydrogen and carbon monoxide is converted into a synthetic crude oil ("syncrude") in a reactor. Syncrude is a mixture of various hydrocarbons (including diesel, kerosene and wax components), which – after FT synthesis – can be further processed into standard fuels (also aviation fuel) via common refinery processes.

Feedstock. Synthesis gas always serves as an initial input material for the FT synthesis. However, the syngas can be provided based on different feedstocks and different processes, which have to be conducted before the actual FT synthesis. There are the Biomass-to-Liquid (BtL) and Biogas-to-Liquid (Bio-GtL) process routes for biogenic SAF.

- In the BtL-process, synthesis gas is primarily produced through gasification of solid biomass (lignocellulose). Examples for this include solid organic municipal waste, agricultural and forestry waste (e.g. straw and residual wood) or energy crops (crops grown specifically for energy use, e.g. wood from short-rotation forestry). The resulting gas mixture from the gasification is then purified to obtain pure synthesis gas.
- Synthesis gas, during the Bio-GtL process, is produced through a reforming of biomethane, a main component of biogas. The biomethane is converted into a gas mixture in a thermo-chemical process, e.g. with the addition of steam, which is then purified into the required synthesis gas.

PtL SAF could also be produced within the FT-process route from water, CO_2 and electricity. In this process, water is converted into pure hydrogen via electrolysis using electricity (from renewable energy sources). The obtained hydrogen, along with CO_2 (from ambient air or biogenic sources such as biogas plants or alcoholic fermentation during bioethanol production) is then converted into synthesis gas.

A further option to produce synthesis gas is through biogas and electricity-based hybrid approaches. Rather than exclusively using water, CO_2, and electricity as input material, which is the case in the PtL-process, part of the required carbon and energy for synthesis gas production is provided via an alternative carbon source (e.g. biomethane). In this multistage plasma process, the biogas can directly be converted into a synthesis gas through the addition of electrical energy and water.

ASTM D7566 Annex 2 – HEFA-SPK

Process Description. The HEFA process primarily bases on the hydrogenation and hydrocracking of vegetable or animal oils and fats converting them into long-chain hydrocarbons. During hydrogenation, ester and double bonds contained in the oils are saturated and oxygen contained in the oil molecule is separated through the addition of hydrogen in form of water. This is followed by a catalyst-assisted isomerization step to improve the suitability as a fuel.

Feedstock. The HEFA process requires plant- and animal-based oils and fats as well as residues containing oil and grease, by-products and waste materials (e.g. used cooking oil).

ASTM D7566 Annex 3 – HFS-SIP

Process Description. In the HFS-SIP process, SAF is produced through a fermentation. Feedstocks containing sugar are therefore fermented by special genetically modified yeast microorganisms. Thereby a long-chain hydrocarbon is produced. The approved biocatalysts are used to produce, among other things, an unsaturated hydrocarbon molecule called farnesene under aerobic conditions. This hydrocarbon is then separated from other fermentation products and then hydrogenated to so called farnesan by hydrogen addition. Farnesan is a pure hydrocarbon molecule with 15 carbon atoms.

Feedstock. In this process, sugar-containing plants (components) such as sugar cane or sugar beet can be used as biogenic feedstocks. Furthermore, starch-containing plant components, such as corn are other possible feedstocks that can be converted into sugar. The sugar containing lignocellulosic feedstocks, such as straw, is an additional material which can be used in the HFS-SIP process.

ASTM D7566 Annex 4 – FT-SPK/A

Process Description. In the FT-SPK/A process, FT synthesis is carried out parallel to the FT-SPK process. The difference, however, is that aromatic compounds are produced in an additional process step (so-called alkylation). Such aromatic compounds are required, for example, to ensure that the sealings between the kerosene tank and the engine of the fuel supply system swells adequately.

Feedstock. The possible feedstocks of the FT-SPK/A pathway are similar to those of the FT-SPK pathway (ASTM D7566 Annex 1 - FT-SPK).

ASTM D7566 Annex 5 – ATJ-SPK

Process Description. In the Alcohol-to-Jet (ATJ) process, alcohols are further processed into aviation fuels. In the first process-step, the chemically bound oxygen of the alcohol molecule is extracted. In a second process step, the resulting alkenes (unsaturated hydrocarbons) are merged to form long-chain hydrocarbons and consequently converted to saturated hydrocarbons in a final step through addition of hydrogen. These hydrocarbons are then separated into individual fuel fractions, primarily gasoline and kerosene, so that the fuel specifications can be safely met.

Feedstock. The feedstocks currently permitted for the ATJ process are the alcohols ethanol and isobutanol. There are, however, efforts made to remove this limitation and allow further alcohols of biogenic origin to be utilized as feedstock as the alcohols are usually obtained from the fermentation of biomass containing starch and/or sugar (e.g. corn, sugar cane, sugar beet).

ASTM D7566 Annex 6 – CH-SK

Process Description. CH-SK SAF is manufactured using the so-called Biofuels Isoconversion (BIC) process. The conversion of the biogenic feedstocks, similar to the HEFA process, takes place in several process steps. The essential step is the so-called Catalytic Hydrothermolysis (CH) in which plant and/or animal oils and/or fats are converted to unsaturated hydrocarbons (alkenes) in a water atmosphere under supercritical conditions. The alkenes, similar to the ATJ process, are then converted into saturated hydrocarbons (alkanes) with the addition of hydrogen and consequently into individual fuel fractions.

Feedstock. The required feedstocks for this process are the same feedstocks used for the HEFA pathway. The BIC process also allows for more heavily contaminated waste fats and oils to be used.

ASTM D7566 Annex 7 – HC-HEFA-SPK

Process Description. The HC-HEFA-SPK pathway is, from a process engineering point of view (nearly) identical to the HEFA method (Annex 2). The underlying difference is the used feedstocks.

Feedstock. Unlike the HEFA process, the feedstocks used for the HC-HEFA-SPK pathway are (solely) biologically derived hydrocarbons and fats. The only approved component presently is a specific algae species (botryococcus braunii).

ASTM D1655 Annex 1 – Co-Processing

Process Description. SAF can be produced from vegetable oils, animal fats as well as Fischer-Tropsch intermediates (syncrude or biocrude) in a "classic" crude oil refinery in joint refining with fossil crude oil. This procedure is also called Co-Processing. As these feedstocks differ from crude oil, special prerequisites arise for the refinery processes; therefore, the blending limit is only 5 % by volume.

Feedstock. The required substances for Co-Processing are plant oils and animal fats as well as Fischer-Tropsch "syncrude" or "biocrude".

Greenhouse Gas and Pollutant Emissions

CO_2-Emissions

The essential difference, from a climate protection perspective, between SAF and conventional (fossil) kerosene lies in a closed CO_2 cycle. As the carbon was previously bound in crude oil below the earth's surface and separated from the biosphere, it had no effect on the climate. However, once utilized, the kerosene pollutes the atmosphere by additional CO_2.

The CO_2 released when SAF is used, was in contrast, already captured from the atmosphere before. This occurs for biogenic SAF during the cultivation of biomass through the photosynthesis processes that take place during plant growth. For electricity-based SAF (PtL-SAF), the CO_2 required for production is provided from biogenic sources (e.g. from biogas or bioethanol plants) or separated directly from the atmosphere using technical processes (direct air capture, DAC). This results in a closed carbon or CO_2 cycle that does not further increase the carbon in the atmosphere.

This type of closed CO_2 cycle, however, only refers to CO_2 emissions released by the use/combustion of SAF in the engine. Aside from the GHG emissions from the final conversion, additional greenhouse gases are released along the entire production and supply chain through feedstock conversion, processing and/or transport. As such, a SAF is not per se completely CO_2-neutral, even if greenhouse gas emissions are (significantly) reduced – especially CO_2 – compared to fossil aviation fuels.

Due to the different CO_2 intensities of the feedstocks (e.g. vegetable oil, wood) and the corresponding conversion processes, the spectrum of SAF shows quite a broad range of achievable emission reductions (Fig. 7). These greenhouse gas emissions often not primarily dependent on the respective production pathway (i.e. the feedstock conversion) but are often essentially determined by the actual feedstock used. The greenhouse gas emissions released by different SAF must therefore be considered both considering the feedstock used and the conversion pathway applied.

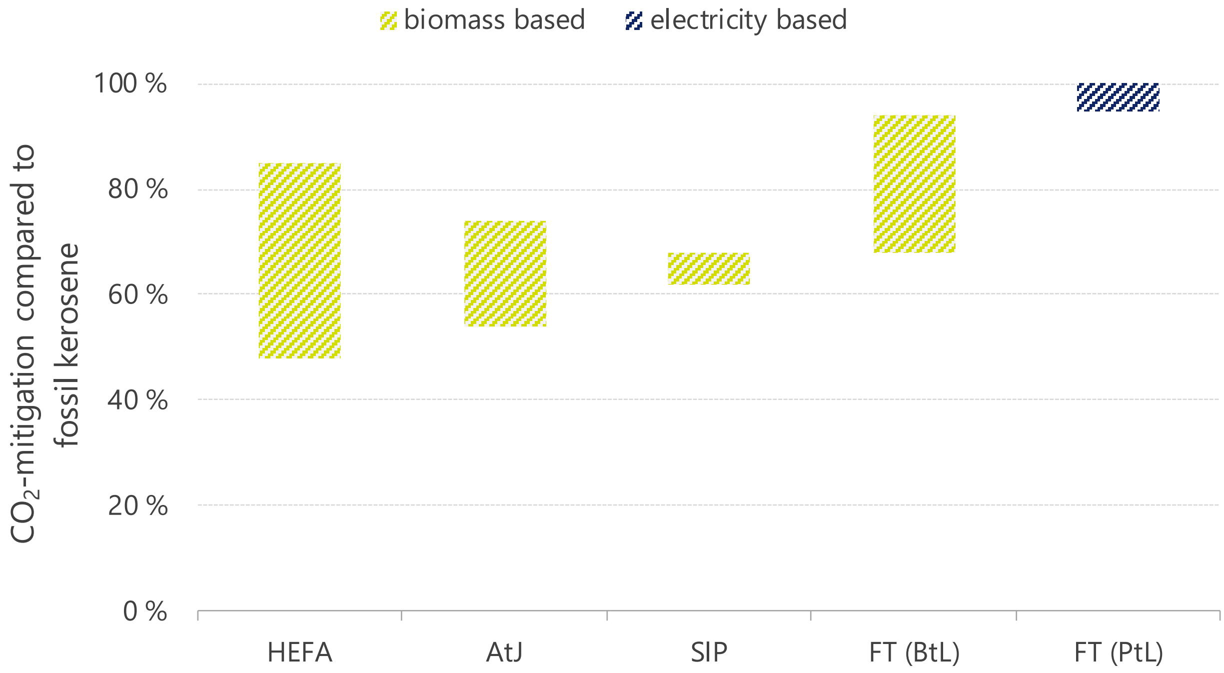


Fig. 7 **CO_2-emission bandwidth of different SAF options**
[EASA 2020; ICAO 2019; Bullerdiek et al. 2019a; Schmidt et al. 2016]

For aviation fuels of biogenic origin, GHG emission reductions of 60 to 80 % and more are (typically) quite possible compared to conventional (fossil) aviation fuels. This is especially the case, if the utilized biomass is derived from residues, by-products and waste. The possible GHG emission savings in the case of PtL aviation fuels, is essentially determined by the source of the electricity and carbon or CO_2 origin. Under the right framework and conditions, PtL SAF can be produced that have close to zero CO_2 emissions. However, this is only true if the used electrical energy originates from renewable energy sources and the CO_2 is extracted from the air or supplied from sustainable biogenic materials. PtL based fuels are therefore, from a climate protection perspective, an essential SAF option for aviation in the long-term.

Minimum emission savings by regulation

In order to ensure that the production and implementation of SAF truly results in reduced GHG emissions and do not excessively induce other negative environmental impacts, they must comply to various sustainability criteria. These criteria are partly defined by national and international regulations. The fundamental European framework which defines the sustainability requirements for SAF in the EU is the Renewable Energy Directive RED or, the revised version (RED II). According to RED II, biofuels for example must demonstrate a minimum GHG emission reduction – depending on the commissioning date of the production facility – of up to 65 % compared to conventional fossil fuels. The specified minimum GHG emission reduction of PtL fuels is 70 %.

Non-CO_2-Effects

In addition to CO_2-emissions, the usage of aviation fuels also generates non-CO_2-emissions which also have a global warming effect. This applies to the usage of both fossil and sustainable aviation fuels (SAF). These are mainly emissions of particulate matter, water vapor, sulfur and nitrogen oxides, which at a cruising altitude, causes atmospheric processes such as formation of aerosols and clouds, affecting the concentration of some atmospheric gases and thus have an overall warming impact on the climate.

An extensive international study shows that only a third of the climate impact of aviation is based on CO_2 emissions and the remaining two thirds is due to non-CO_2-effects. Regarding the latter, contrails and the induced cirrus clouds are a significant component of the non-CO_2-effects. Due to such non-CO_2-effects, the use of low-emission or potentially "emission-free" aviation fuels (e.g. PtL SAF) therefore, also leads to a global warming effects or radiative forcing effects, even if it is still more limited compared to fossil kerosene [aireg 2020].

Pollutant Emissions

Furthermore, in addition to the global environmental impacts of climate gas emissions, local emissions or local effects, when it comes to the usage of SAF, are also relevant to the air quality. Particulate emissions specifically are in the focus, as the released climate impacting atmospheric soot, can lead to negative health conditions once it accumulates on the ground. These soot particles released from an aircraft engine, are smaller than 100 nanometers, thus being ultrafine particles. Once inhaled, the particles can penetrate deep in the human lungs (alveoli) and be deposited. The influencing factors of the soot emissions are diverse. Innovative engines can contribute to lower particulate emissions through decreased fuel consumption or by means of having a more advanced combustion chamber design (e.g. lean-burn engines). Another essential criterion is the fuel used or its molecular composition.

Studies show that the mass of the released soot from aircraft engines approximately correlates with the hydrogen content of the fuel. The majority of SAF processes produce synthetic fuels with a low aromatic content and a correspondingly high hydrogen content. A demonstration of the implementation of renewable paraffin at Leipzig/Halle Airport (DEMO-SPK) experimentally proved that by switching from a fossil kerosene to a mixture of SAF resulted in a 70 % reduction of the soot mass and approximately 60 % in the number of particles – while using the available infrastructure and currently accessible engine technologies.

An added benefit of using SAF is the reduction of volatile particles, as pure SAF does not contain sulfur. The usage of SAF, however does not lead to a significant change in the gaseous emissions such as carbon monoxide or nitrogen monoxide. Such air pollutants arise through the burning process of fuel and can only be avoided or at least reduced by improvements on the engine or combustion chamber.

Furthermore, the enhancement of fuel properties to achieve the most efficient use of the available fuel capacities ("fuel design") is possible through the appropriate selection of fuel components from fossil and alternative sources. The implementation of SAF therefore provides the opportunity to produce fuels with optimized attributes. This potential however is currently not being worked on due to limitation reasons of production capacity and logistics – and because of the especially higher costs for SAF [aireg 2020].

Barriers to SAF Production and Deployment

Although eight pathways are already approved by ASTM to produce sustainable aviation fuels, their broad market implementation is so far still missing (globally and regionally). This is the case although various SAF options have been technically tested and their operational readiness demonstrated in multiple projects. Yet, the production of SAF is limited to very few producers and extremely small quantities. In 2017 the share of SAF in the EU was only about 0.05 % and only 0.1 % on a global scale. Overall, SAF has barely exist in the global aviation fuel markets so far.

A global market ramp-up of SAF is hampered by various technical, economic, operational and acceptance-related factors. This virtually non-existent market scale-up is primarily based on a combination of two fundamental factors. These factors being a lack of economic viability of SAF options due to (extremely) high production costs compared to fossil kerosene and (in combination) with a lacking target-oriented regulatory framework.

High SAF Production Costs

The production costs of SAF are so far significantly higher compared to fossil kerosene, although they have near identical technical (usage) properties. SAF, at present, are about 2 to 5 times more expensive (in some cases considerably greater) than fossil fuels (Fig. 8). While HEFA based SAF, especially from waste oils and fats, are currently still at least twice as expensive as fossil kerosene – but in some cases already available on the market in larger amounts – the price range for other SAF options is even higher.

The higher production costs of SAF and consequently higher fuel prices on the market essentially result from costly (biomass) feedstocks, complex production facilities and the current production in limited volumes only. To further reduce production costs and further costs along the SAF supply chain, technological learning and large-scale production (economies of scale) must be achieved. This can only be achieved by an appropriate SAF market ramp-up and appropriate SAF volumes.

Furthermore, several technologies for the production of SAF are at a development phase between pilot/demonstration plants and first (small-scale) industrial applications. A further scale-up of production plants requires (exceptionally) high investments, while the demand for SAF is difficult to estimate without the appropriate regulatory framework. Such framework conditions and the overall situation are clearly unattractive for investors, i.e. a lack of investment capital for the construction of corresponding SAF production plants is the consequence and different SAF technologies might only reach commercial viability – if at all – at a slowed pace.

Overall, a classical hen-and-egg problem exists. The high SAF costs are in part a consequence of a lacking demand for SAF. The demand, in turn, will not increase as long as there is no cost parity of SAF with fossil aviation fuels (as long as SAF and fossil kerosene are in a competitive situation). A SAF market injection would be further hampered if other countries do not implement corresponding framework conditions for SAF climate protection requirements. This would further delay the ramp-up of SAF production facilities and thus the usage of cost reduction potential for SAF, and overall only consolidating the current situation.

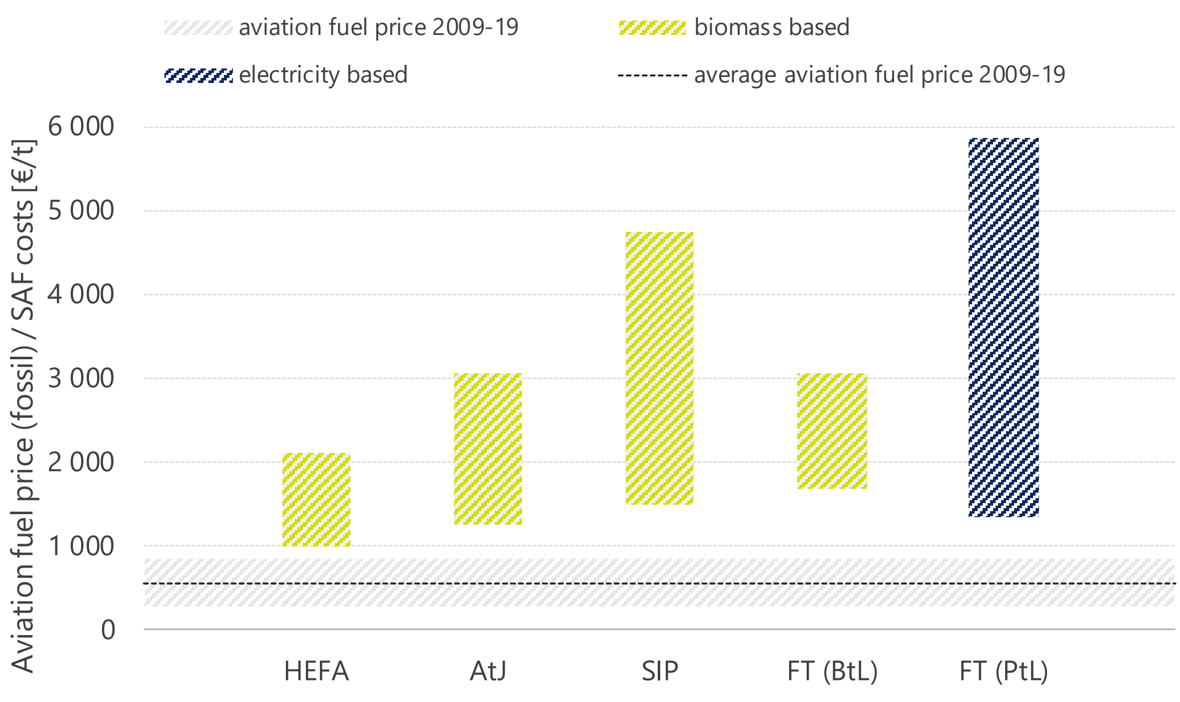


Fig. 8 **Bandwidth of fuel prices/costs of fossil aviation fuel and different SAF options**
[Neuling 2019; ICAO 2017; Bullerdiek et al. 2019a; Timmerberg et al. 2019; Pavlenko et al. 2019; Dietrich et al. 2017; Jong et al. 2015; Agora und Frontier Economics Ltd. 2018; Brynolf et al. 2018; Hobohm et al. 2018; Schmidt et al. 2016]

However, even if all cost reduction options are completely exploited, a cost parity with fossil kerosene may not be reached for all SAF options and feedstock options available (particularly if future kerosene prices correspond to the past kerosene price levels). For this reason, adequate supply-side instruments (e.g. subsidies / tendering models) and/or demand-side instruments are essential for a broad SAF market introduction.

Lacking Regulatory Framework for SAF

The "rules of the game" in global aviation are defined by a set of various national and international regulatory frameworks and guidance instruments which partly also include SAF. However, so far, the environmental advantage of SAF is not effectively integrated in the economic calculations of a commercial airline by existing legal frameworks. Airlines, therefore, have yet no true incentives to (extensively) implement sustainable aviation fuels in their day-to-day operations. The main instruments and regulatory frameworks that (partially) influence the economic activities of commercial air transport in Germany are further presented in the following.

Air Traffic Tax. In Germany, the air traffic tax was introduced in 2017 to incentivize environmentally friendly mobility and, simultaneously, help to consolidate the federal budget. The air traffic tax does not depend on the actual distance of a flight. It is charged for three different flight distance classes per departure of a passenger in Germany. The air traffic tax, in theory, generates an incentive to avoid travel (reduced air traffic volume) or modal shift (to less expensive transport options). These two incentives could result in a climate-friendly effect. As the price of the tax is not determined by the emitted climate gases but is the tax is charged per passenger, it does not create any actual incentives to take climate-friendly measures in air traffic. As a result, the implementation of sustainable aviation fuels, in conjunction with other climate gas-reducing measures (e.g., improved seat utilization or more efficient aircraft) are not fostered.

European Union Emissions Trading System (EU ETS). Following the integration into the European Emissions Trading System (EU ETS) since 2012, airlines need to purchase emission allowances (European Union Aviation Allowance, EUAA) for flight related emissions within the European Economic Area. Such allowances are partially allocated to airlines for free. However, this unpaid share only covers a portion of the absolute emitted emissions. Additional emission allowances must be purchased via auctions or bilateral trading.

In contrast to fossil kerosene, sustainable aviation fuels are considered in the EU ETS with zero emissions, provided they meet the sustainability criteria of the Renewable Energy Directive (RED II). Integrating the environmental characteristics of sustainable aviation fuels into the economic calculations of an airline, gives an incentive to reduce climate gas emissions through utilization of SAF. However, in the end there is only a real (economic) motive

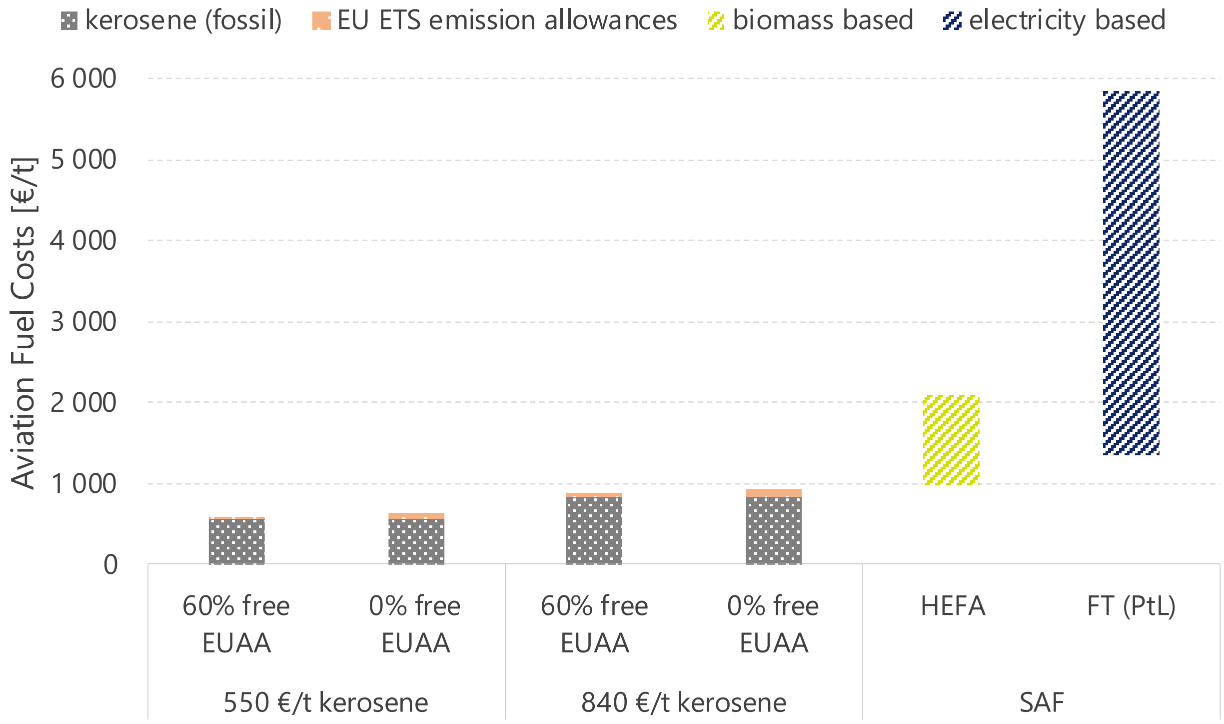


Fig. 9 **EU ETS related aviation fuel costs of fossil kerosene, HEFA SAF, and PtL SAF**
(Neuling 2019; Pavlenko et al. 2019; Jong et al. 2015; EEX 2019; Agora und Frontier Economics Ltd. 2018; Brynolf et al. 2018; Timmerberg et al. 2019; Schmidt et al. 2016, own calculations)

for airlines to use SAF instead of fossil kerosene in their day-to-day operation if the total costs of using SAF are lower than the cost for a usage of fossil kerosene. Within the EU ETS this means that the fuel price to be paid for SAF must be lower than the price of fossil kerosene plus the cost of EU ETS emission allowances (Fig. 9)

Figure 9 shows that a cost parity between fossil kerosene and SAF is not realized within the EU ETS (at current fuel and CO_2 price levels), as the EU ETS related fuel costs of fossil kerosene are only marginally increased by the purchase of EU ETS emission allowances. Even if an airline had to buy all EU ETS emission allowances (i.e. no free emission allowances, 0 % free of charge), competitiveness for SAF would not be achieved. In conclusion, the EU ETS will most likely not be able to properly incentivize the use of SAF in Germany or the EU without significantly higher price levels of emission allowances.

CORSIA. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a market-based climate compensation instrument (offsetting instrument) to allow for a carbon neutral growth in international aviation from 2020 onwards. Airlines are required through CORSIA to offset their greenhouse gas emissions through certified emissions reductions (known as CORSIA offsets). These certified emission reductions are realized outside of the aviation-sector in climate protection projects and must be purchased by an airline for those emissions that exceed a certain emissions cap (baseline) (2019 emissions level). CORSIA only applies to international flights as domestic emissions are exempted from this instrument.

Comparable to the EU ETS, SAF can be used and accounted for by an airline in CORSIA to reduce greenhouse gas emissions and thus reduce the amount of CORSIA offsets to be purchased. Therefore, SAF must have a minimum (net) greenhouse gas emission reduction of 10 % throughout its entire life cycle compared to fossil kerosene. For CORSIA, similarly to the EU ETS, there is only an incentive to use SAF, if the use of a sustainable aviation fuel is economically more efficient than using fossil kerosene. Therefore, in addition to fuel costs, the respective amount of CORSIA offsets must be considered.

The price of CORSIA offsets could, especially during initial phases, be about the same or even lower than the price of EU ETS emission allowances. Even under the frameworks of CORSIA, it would adversely be very unlikely that the large-scale use of SAF would be significantly promoted. In addition, only offsets for CO_2 emissions above the corresponding baseline have to be purchased by the airlines.

European Directives. The implementation of renewable energies in the EU´s transport sector is primarily regulated by the Renewable Energy Directive (RED) or its revision (RED II) and the EU Fuel Quality Directive (FQD).

RED (II). The RED II obliges EU member states to achieve a minimum share of 14 % of renewable energy in the transport sector by 2030.

Sustainable fuels which are used in aviation and maritime transport can be accounted to the 14 % target by Member States and with a multiplier of 1.2 (related to their energy content and provided the fuels are not produced from food or feed crops). However, if renewable fuels originate from biogenic waste and residues (e.g. used cooking oil), a double counting related to their energy content is possible. According to the RED II framework, this results in an accounting factor of 2.4, if the feedstocks are used for the production of sustainable aviation fuels. This leads to a certain incentive to use SAF over other (fuel) options to achieve the RED II target. However, apart from this incentive, RED II does not contain any binding requirement for the use of SAF.

The RED II must be implemented into German law by mid-2021 and as such the corresponding legislative procedure has been initiated. Based on previous considerations, a quite limited quota could be implemented by law for the use of electricity-based SAF in aviation. Furthermore, the market injection of sustainable aviation fuels should be incentivized by an "opt-in" mechanism, similar to the regulation in the Netherlands.

FQD. The EU Fuel Quality Directive (FQD) requires a minimum reduction of greenhouse gas emissions induced by fossil gasoline and diesel fuels that are supplied to the market of 6 % by 2020 (compared to the EU average in

2010). However, similarly to RED II, these requirements do not apply to aviation fuels. The FQD therefore does not create an incentive or binding requirement to use SAF.

Conclusion. Overall, airlines do not have the necessary incentives to use SAF apart from reputational and marketing reasons. Already implemented mechanisms in Germany, the EU or internationally, such as the aviation tax, the EU ETS or CORSIA, do not create sufficient stimulus for a large-scale use of SAF. Although the environmental advantage of sustainable aviation fuels (lower greenhouse gas emissions compared to fossil kerosene), is already considered economically within the framework of the EU ETS and CORSIA, the resulting (financial) incentive is not sufficient to create a commercial viability for SAF. The competitiveness and thus potential large-scale use of SAF has, as of yet, been dismissed due to the significant differences between the market prices for fossil kerosene and the production costs of sustainable aviation fuels. Furthermore, the absence of suitable regulatory incentives or legally binding regulations (e.g. mandates) – as in road transport – hamper a broad SAF market injection.

National Implementation of RED II. In the process of implementing the RED II, primary binding targets for the use of SAF as well as supply-side support mechanisms are being reviewed in some countries and are also proposed in the present draft for the implementation of RED II into German law. Moreover, individual European states have fostered the use of SAF by law in the form of SAF mandates, which (in part) differ greatly in their design and requirements. Whilst certain measures are executed at best at national level – at least in the EU – and an inhomogeneous supporting framework for SAF is created, the basic European directives on climate protection in the transport sector, however, have not yet considered sustainable aviation fuels on a proper regulatory level.

Overall, there is no adequate planning security for a market development for SAF so far. This, however, could change with the implementation of RED II into German law, if biogenic and electricity-based SAF are taken into account. Current and future producers urgently require a reliable market in the long term, to acquire capital and make investments in plant construction, and thus also use cost reduction potential by accelerating learning curves. Alternatively, there is a risk that feedstocks for the production of fuels or other products are dedicated to other sectors (e.g. chemical industry / green chemistry).

ReFuelEU Aviation. The promotion and use of SAF at European level, is currently being intensively discussed within the framework of the "ReFuelEU Aviation" initiative. It is a crucial element of the “EU Green Deals” and the “Sustainable and Smart Mobility Strategy” to accelerate the market ramp-up of sustainable aviation fuels. After various round table discussions being carried within the frameworks of the ReFuelEU Aviation initiative and, through a public consultation, several regulatory packages of measures to promote sustainable aviation fuels for the EU have been developed. Multiple SAF mandate options in particular, were thereby discussed as possible steering instruments. However, the different proposed drafts represent different technical, environmental, economic and regulatory challenges, opportunities and risks. The completion of a selected approach and the completion of various mandate components, e.g. the scope, type of mandate (volume-based or GHG reduction related), the obligors (suppliers or airline) or the exact compliance mechanisms, are still pending [EC 2020b, 2020a]. Sor far, the utilization of crop biomass for a mandate fulfilment is exempted in all current drafts to incentivize actual sustainable SAF supply chains and to realize a high acceptance in society.

Necessary Actions. Consequently, if effective climate protection is to be realized in commercial aviation in a timely and substantial manner, target-oriented support mechanisms are required to create planning security for SAF projects and a suitable economic competitiveness of biogenic and electricity-based SAF.

This unlocks the great opportunity for Germany as an industrial location to embrace a pioneering role in the market ramp-up of SAF and thus, in the medium term, evolve into a technology provider for plant technology required for a de-fossilization of commercial aviation.

aireg Roadmap for the Deployment of Sustainable Aviation Fuels

Background and Objective

Sustainable aviation fuels have an immense potential to become the pioneers for the reduction of climate gas emissions in aviation. This applies to both current and future aircraft fleets, which – in a lengthy transition period – will at the very least, continue to rely on liquid kerosene. To take advantage of the potential of SAF, to promote the construction of production plants and to create suitable (economic) conditions for the use of SAF, tremendous efforts and coordinated planning are of the utmost importance.

While the overall quantity of current SAF is extremely scarce, and as SAF are available on the market solely biomass based, their production capacity is expected to expand to over 10 million tons annually in the 2020s. The latest prognosis from the USA and Asia even propose that yearly capacity could potentially rise to 30 to 40 million tons in 2030. In the course of this production increase, it is expected that the cost of SAF will settle at about twice the price of fossil sourced kerosene. This, however, will greatly depend on the subsequent alterations of fossil crude oil prices.

The decline of greenhouse gas emissions of biomass based SAF, especially those derived from waste, residues and by-products, are considerable. As an outcome of implementing them, 80 % less CO_2 emissions (CO_2 of fossil origin) and up to 70 % less particulate emissions can be emitted.

Unlike in Europe, with a few exceptions, US airlines are already incorporating the limited SAF quantities available on the market in their regular operations. This is not least owing to the favorable regulations to reduce the costly prices, but moreover, that European airlines are comparatively reluctant to use SAF due to a lack of regulatory incentives. Without greater production volumes that are more accessible on the market, a substantial business for SAF will expectedly not develop in Europe or Germany. Furthermore, the lack of competitive utilization costs (at least compared to fossil kerosene) and, above all, the absence of the appropriate regulatory framework to legally regulate the use of renewable fuels in aviation, obstructs the construction of a successful market for SAF.

If the German (and European) aviation sector intends to make a consequential contribution to aviation's climate protection goals as well as the European and German climate goals for the transport sector, that have been set as globally binding under international law, the production of enormous quantities of SAF to be used in commercial aviation is an unavoidable requirement.

For this need for action, the roadmap developed by the aireg members illustrates a possible development path taking into consideration technological, environmental, economic and regulatory framework conditions and prerequisites. This roadmap serves as an objective, to strategically, systematically and comprehensively advance the implementation of SAF and continuously evaluate the course of development, in Germany and especially in Europe as a whole.

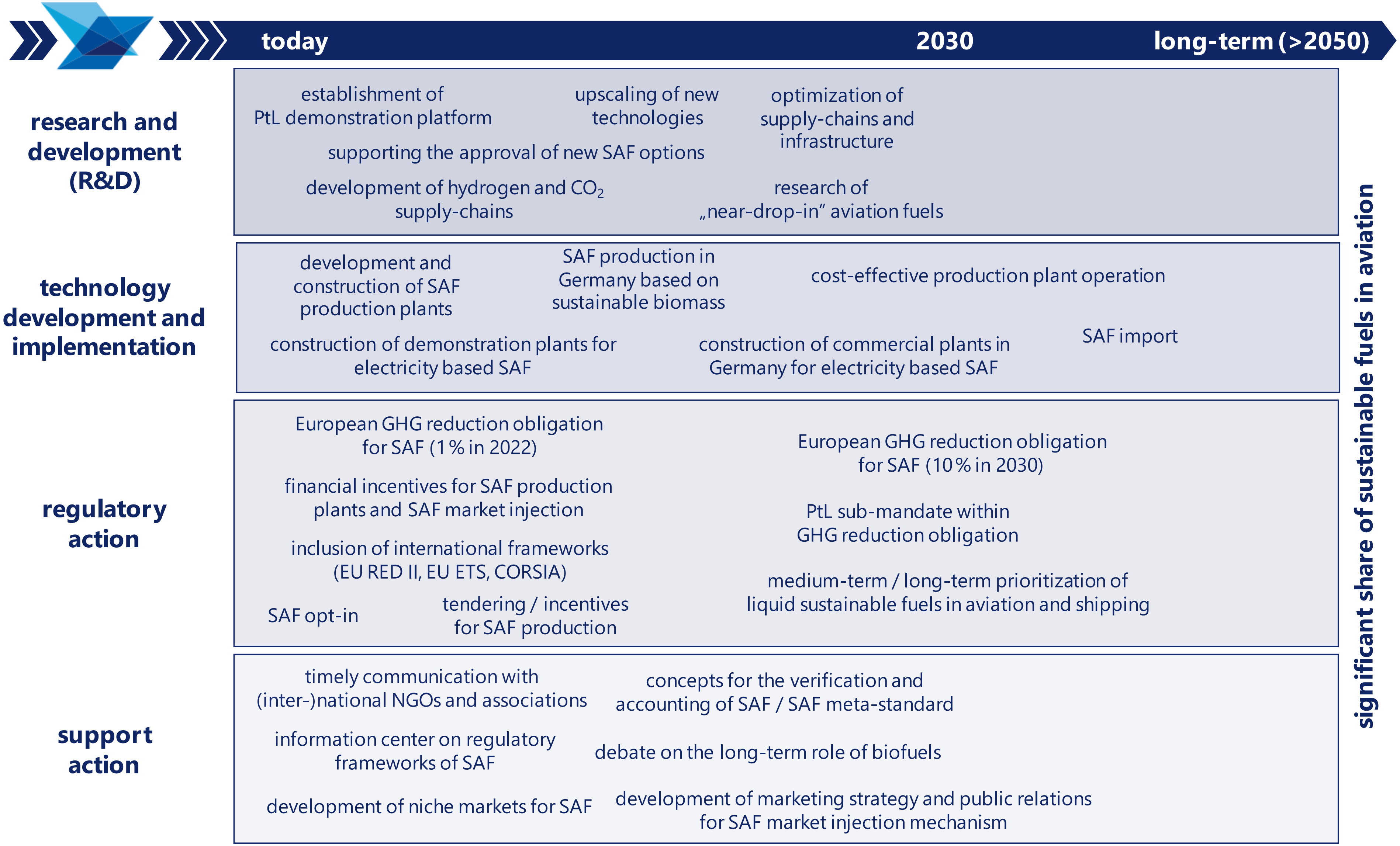
The measures contained therein include the research and development (R&D) of SAF-production technologies, the (industrial) technological improvement and execution of SAF, the establishment of suitable regulatory framework conditions as well as supporting measures. This roadmap thus includes concrete implementation proposals until 2030 as well as recommendations exceeding 2030 and potentially have an impact until 2050.

Members of aireg offer to cooperate with politicians at federal and state level as well as other stakeholders from industry and science to collaboratively promote the urgently required market ramp-up of sustainable aviation fuels and to execute it at the earliest opportunity.

If the German and European aviation industry intends to significantly contribute to the climate protection goals of aviation and the transport sector, a large-scale use of sustainable aviation fuels will be required, taking into account all sustainable feedstock options.

For this requirement, the aireg roadmap presents a possible development pathway.

Fig. 10 aireg Roadmap for the Deployment of Sustainable Aviation Fuels



Research and Development (R&D)

These measures intend to prepare the ramp-up of SAF technologies that are still considerably distant from commercial viability. This requires, among other things, the assembly of the initial semi-industrial plants with which initial experience can be gained for a successive commercial operation. This should be performed in close collaboration between science and industrial stakeholders. With the measures contained in this category, it is also imperative to determine other means to facilitate the supply of feedstocks for a large-scale SAF production (e.g. hydrogen and CO_2 for electricity-based fuels).

Establishment of a PtL demonstration and research center in Germany

A limited potential of biogenic feedstocks will most likely restrict the prominence of biogenic SAF in aviation in the long-term, even if they are inevitably required particularly for a short- and medium-term SAF ramp-up. Non-biogenic aviation fuels, especially PtL fuels, will therefore have to play an essential role in order to defossilize air transport in the medium- and long term. In order to make these options – which from a scientific perspective are still far from large-scale industrial applications – available in the initial phases and in sufficient abundance, the required production processes or the respective engineering for these processes must be developed in advance and brought to market maturity. This necessitates a considerable public (funding) support to ensure that learning curves are successfully passed, and the production technologies will be accessible for the market.

The establishment of a research and demonstration center (as a pilot plant / demo plant) for PtL fuels should, in this case be set up, if possible, under the general management of an existing (federal) research organization, with the goal of advancing and supporting a scale-up or market maturity of PtL fuels. In the forthcoming procedures, networking and assembling of existing competences from research and industry in Germany should also be put into effect, i.e. a close cooperation between research and industry must and should be strived for.

The research and demonstration center should contain the establishment of a semi-industrial production facility with an annual production of about 10,000 tons of sustainable PtL kerosene. While initially only the Fischer-Tropsch technology can be used for this purpose – also because of the existing experience with this technology – since only this technology route has so far been approved for aviation according to ASTM, other technology routes (e.g. methanol synthesis) must also be further developed for their industrial suitability. In this respect, this demonstration center can also play a coordinating and integrative role for activities at other locations in Germany.

Development of hydrogen and CO_2 supply-chains

A significant challenge for the large-scale production of synthetic, electricity-based fuels is a reliable, efficient and sustainable supply of hydrogen (H_2) and (sustainable) carbon dioxide (CO_2) in sufficient quantities.

The production of hydrogen can be accomplished in various processes; one such promising and scalable production option for so-called "green" hydrogen, being water electrolysis. During this process, water is separated using electrical energy from renewable sources into hydrogen and oxygen. As a result of the extreme energy demand and the corresponding immense share in the total expenses of fuel synthesis – regions and locations with a particularly high potential for producing and exporting renewable energies are essential for cost-effective hydrogen production. That is why the German government has, within the scope of the national hydrogen strategy, increasingly focused on locations in the MENA region, in South Africa and in South America. In order to reduce the cost fluctuations of renewable energies a combination of wind power and photovoltaics is predetermined. As such this also enables the storage capacities, which are required to guarantee a constant supply of hydrogen, to be smaller in design. Potential storage possibilities include hydrogen storage facilities in the form of pressurized tanks and, in the future, salt caverns, pumped storage and also batteries to complement the storage of electrical energy.

A possible option for supplying CO_2 from sustainable sources is the use of biogas containing carbon dioxide. The CO_2 is released as a by-product when the biogas is processed in a biogas plant, in order to transfer the contained biomethane into the gas grid as "green" gas. In these cases it would also be required to set up a respective supply infrastructure so that CO_2 can be distributed from various sources and/or locations as flexible as possible to further PtL production sites.

If CO_2 is extracted from the ambient air (Direct-Air-Capture) through atmospheric deposition, it could be provided for at the site of the PtL plant. The issue with this option, however, is the low concentration of CO_2 in the ambient air. This results in a high energy demand and correspondingly complex plant technology to be able to extract a certain amount of CO_2.

In conclusion, it is consequently necessary to investigate both the prospects of hydrogen supply via water electrolysis and the availability/development of sustainable CO_2 sources as well as their respective potentials for supply in order to facilitate an industrial PtL production.

Supporting the approval of new SAF options

So far, for SAF the drop-in approach is primarily being pursued. This means that the specifically approved SAF options are expected to be utilized, along with conventional (fossil) fuel, in commercial engines and the existing fuel infrastructure (i.e. pipeline systems, airport fuel tanks or the airport fueling infrastructure) without technical modifications. To fulfil these requirements, there are rigorous and precise test conditions set in place as part of the approval process to ensure that the essential property spectrum of an SAF option coincides with the qualities of conventional (fossil) fuel.

Due to safety reasons, the requirements for the properties of aviation fuels are extremely high and hence are defined by multiple specifications and standards (e.g. ASTM D1655, ASTM D7566, DEF STAN 91-91). The approval of new SAF within the framework of these specifications and the possible approval of SAF options that can be used without blending with standard-compliant aviation fuels (100 % SAF), is usually a multi-year and cost-intensive process in which various authorities and industry stakeholders are involved.

To promote a wide spectrum of SAF options, the approval of future fuels should therefore be largely supported. Such support can be accomplished by assisting in communications with approval authorities, exchanging information and data, preparing the necessary documentation for the certification process, and exchange information with aircraft and engine manufacturers. Previous experience with already approved SAF options as well as the contribution of current globally acquired research results can also beneficially complement ASTM's optimization efforts.

Upscaling of new technologies

The upscaling of today's plant scales is an absolute necessity so that new SAF technologies can be utilized for electricity-based SAF production (e.g. new electrolysis processes, new synthesis reactors) in an economically viable way. This can be achieved by supporting the upscaling of these technologies from a laboratory or experimental level to an industrial extent. During such a ramp-up, smaller PtL plants should be initially built so that learning and experience curves can be passed and experience for future commercial production of PtL can be gathered. The construction of smaller plants should, however, be commenced at the earliest opportunity, as certain (potentially longer) time periods must be taken into consideration (e.g. for planning and approval of processes).

Optimization of supply-chains and infrastructure

Despite the fact that much of the existing aviation fuel infrastructure can be used practically without limitation for sustainable aviation fuels, certain adjustments and extensions to this infrastructure will be essential. This applies, for instance, to modern SAF facilities in further decentralized locations to connect to existing infrastructure. Particularly for PtL production, feedstock supply chains (e.g. for hydrogen and CO_2 transport) as well as parts of the processing infrastructure (e.g. existing refinery plants) must be adjusted and optimized to meet the requirements for the large-scale use of SAF.

Analogous to the large-scale use of SAF at (international) commercial airports, SAF could further be used within the general aviation segment. The application of SAF in these niche segments, particularly during market ramp-up phases, can be advantageous as this segment does not entirely operate at large (international) commercial airports, the inclusion of SAF must therefore also be made available at smaller airports.

Research of „near-drop-in“ aviation fuels

Drop-in fuels meet all technical specification requirements of fossil-based JET A-1 and JET A fuels as they are compatible with today's existing infrastructure and aircraft fleets. This compatibility extends from older aircraft and engine types to modern aviation concepts and engine technologies. At present drop-in can only, however, be blended with conventional aviation fuel (kerosene) to a maximum percentage of 50 %. This in turn inhibits the achievable greenhouse gas reductions and a possible entire substitution of fossil aviation fuels (which should be pursued for climate protection considerations).

In addition to drop-in fuels, there are also so-called "near-drop-in" fuels. In principle, these permit higher blending limits, but in some cases require minor modifications to certain aircraft components (e.g. sealings in the fuel system). These near-drop-in fuels can be used up to 100 % in modern engine technologies, which among other things substantially increase the achievable GHG emission reductions in contrast to drop-in fuels. Near-drop-in fuels can also reduce pollutant emissions and maintenance costs.

In light of this, the ASTM qualification and usage of near-drop-in fuels has to be accelerated parallel to the subsequent development and approval of drop-in fuels.

Technology Development and Roll-Out

The following measures are intended to shift various SAF technologies to a commercial, large-scale industrial standard. Due to the lack of economic competitiveness on the SAF market, a high capital demand and long waiting periods, among other things, are required for the upscaling of production capacities. The ensuing measures are also aimed to ensure the availability of sufficient SAF quantities at German airports, despite the fact that the production potential in other countries, regions or continents may be significantly greater.

Development and construction of SAF production plants

The path from process development to the operation of a commercial SAF production plant pursues several progress steps over several years.

After fundamental research (i.e. ramp-up from laboratory scale synthesis to pilot plant), the planning and construction of the large-scale technical plant can commence. For this objective, a Process Design Package (PDP) is created for a given industrial production capacity, which describes the process technology needed, independent of the plant's location. It contains the primary structure of the facility with the process stages, which are determined by the corresponding mass and energy balance and establishes the prerequisites for the infrastructure of the site (such as input materials, energies and operating resources, labor, and space requirements).

The location of the production plant is then defined in the next crucial step. Ideally, the plant is constructed at an existing chemical or refinery site. In that case the existing infrastructure can already be utilized, and prior specialized personnel can be employed. Additionally, the acceptance of residents / locals can safely be assumed, and a simplified and thus significantly shorter environmental impact assessment can be executed. Furthermore, the availability of a renewable carbon and CO_2 source is vital for the plant's production of electricity-based SAF.

On the basis of this location evaluation, preparation of a feasibility analysis can be formed, considering the regional conditions. In this context, variants of the plant layout and the integration into the infrastructure are reviewed and backed up with a corresponding cost estimate and time schedule. This can already be executed in correspondence with the location analysis.

After the basic foundations have been set, the basic engineering phase follows, under which and among other things, crucial design parameters, energy and mass balance, necessary machines and apparatus, and the required automation technology are determined. Additionally, the assembly and construction of steelwork and piping technology as well as safety measures are planned for.

The results of the basic engineering phase are then incorporated into the approval procedure following the necessary hearings and public participation in consideration of existing law and regulatory requirements. Customarily, the detail engineering phase follows after approval has been granted, in which case detailed designs of machines, apparatus, measurement and control technology as well as the precise planning of piping, construction and steelwork are outlined.

The necessary procurement activities are already initiated during detailed engineering and as such particular consideration must be given to the determination of equipment with long delivery times.

Simultaneously, the construction and installation of the SAF production plant also commence during this phase and thus the recruitment and training of the operating personnel must begin at the same time.

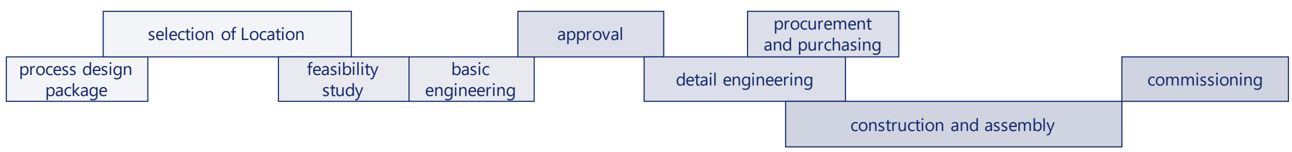


Fig. 11 Sequence scheme of planning and construction of SAF plants

After completion of the production plant, the commissioning activities are started, which conclude with the successful performance run and handover of the plant (including as-built documentation) to the operator. All things considered, it can be expected that a lead time of at least 3.5 to 5 years is necessary to completely engineer, construct and commission a SAF production plant, of course considering any planning work already carried out in advance. The construction of a plant must therefore be initiated at the earliest stage possible as SAF can only be made available several years following that establishment.

SAF production in Germany based on sustainable biomass

Existing plant capacities for the production of sustainable, biogenic fuels can only provide for a limited quantity of SAF. Moreover, they are almost exclusively located in a different country and in order to keep a corresponding know-how in Germany and to build up plant capacities for a national supply of sustainable, biogenic SAF, it must be examined that existing biofuel plants be upgraded for the supply of SAF. This would (i) achieve additional market availability of corresponding sustainable kerosene, (ii) gain further experience with an industrial plant operation in Germany, which can then be transferred to further projects if necessary, and (iii) provide significant SAF volumes for German and European air traffic.

In such a case, suitable de-fossilization options must also be provided for sectors / applications that are no longer served by modified/repurposed biofuel infrastructure but still have a necessity for non-fossil fuel options – for example, road-based transportation.

Construction of demonstration plants for electricity based SAF

PtL fuels as well as hybrid processes based on feedstock combinations have the potential to make a decisive contribution to environmentally friendly and climate-neutral air transport. At present however, apart from a few laboratory or small-scale plants (i.e. production output quantity on a liter or kilogram scale), no larger-scale plants are in operation. These are, nonetheless, imperative to accelerate the learning curve in the production of such fuels and thus determine cost reductions in production, which is necessary for a (timely) market entry of sustainable aviation fuels.

The construction and operation of one or more PtL demonstration plant(s) on an industrial (demonstration) scale (at least 10,000 to 15,000 metric tons per year), at a cost of approximately 150 to 200 million euros each, can establish a technological pioneering role for Germany that is essential in terms of industrial policy, i.e. will form the foundation for sustainable added value.

Construction of commercial plants in Germany for electricity based SAF

After a successful demo operation, the technology then needs to operate on a (large) industrial level in order to (i) scale-up the technology, (ii) gain experience with an industrial plant operation in order to pass it along to future projects, and (iii) recognize the first major utilization offers for German and European air traffic.

Cost-effective production plant operation

Due in part to the lack of a regulatory framework, it is as of yet uncertain how the widespread market launch and market ramp-up of electricity-based synthetic kerosene can succeed. On the one hand, electricity-based fuels are costly to produce and will therefore remain far more expensive than fossil aviation fuels in the foreseeable future. Furthermore, the learning curve in the production of such fuels must first be passed in order to define a market entry; the latter must be legally supported so that a market can be created at all. From a certain point on, it must then be possible to economically operate the plant under the defined framework conditions.

SAF import

In the long term, the production potential for sustainable and cost-efficient aviation fuels in Germany or the EU is limited when put in contrast to the country's or union´s demand. High capacities for the production of renewable fuels and kerosene are, irrespective of the aforementioned limitation, currently being constructed in North America and in individual Asian countries. In order to provide sufficient quantities of sustainable aviation fuels in Germany and in the EU, it is therefore imperative to import biogenic or electricity-based feedstocks and fuels from regions with a respectively high potential of renewable energies. This can also be viewed with economic advantages. However, such an import requires transparent and traceable verification of compliance with sustainability criteria in the countries of origin before it is used in aircraft. This requires the essential timely exchange with national and international NGOs and associations and also includes the various governmental organizations responsible for global air traffic.

Regulatory Measures

Effective regulatory measures must be taken to create a framework that removes the main market barriers for SAF (a lack of economic competitiveness). Simultaneously, it must be ensured that a sufficient SAF supply can be made available. Therefore, regulatory measures must consider both supply-side and demand-side measures, while different SAF options need to be promoted as comprehensively as possible. In other words, both sustainable biogenic SAF options and sustainable electricity-based SAF options should be supported with equal emphasis.

Financial incentives for SAF production plants and SAF market injection

As no (larger) SAF production plants have been built or are being operated in Germany to date, it has not yet been possible to pass learning and experience curves to reduce production costs for SAF. In order to realize the immediately needed market ramp-up, the government must therefore implement appropriate financial support measures that favor and ideally ensure a fundamental build-up of SAF production capacities. Favorable loan models, tendering models and/or tax incentive models for fuel producers and suppliers should therefore be considered and preferably executed at European level. For the concrete development and design of supply-side mechanisms, close cooperation between science, industry and ministries should be pursued so as to directly eliminate information gaps and disparities at the earliest stage possible.

Inclusion of international frameworks (EU RED II, EU ETS, CORSIA)

Aviation is an international industry. In addition to individual national steering measures, there are also inter- and transnational measures or agreements to reduce aviation emissions. In order to execute the proposed measures of this roadmap, it is of utmost importance to thoroughly examine their regulatory compatibility with regard to already existing measures, such as the EU ETS or CORSIA, or to design them accordingly in a regulatory compatible manner.

Tendering / Incentives for SAF production

The international tendering of production capacities appears as a promising option after passing a demonstration phase to execute a market ramp-up for SAF. PtL production capacities in particular should, under a tender model, be tendered in multiple rounds, for which producers can apply. The producers then receive (fixed) (additional) compensation for a fixed period to ensure competitiveness with conventional (fossil) aviation fuels.

These mechanisms can be designed in such a way that potential producers can benefit from a predefined budget of subsidies, while the subsidies or grants are awarded depending on the specified SAF production costs or their GHG mitigation costs. In this context, tendering models must be configured in a manner in which the greatest possible range of SAFs can be promoted so as to avoid a one-sided publicity of scarce SAF options. Once again, close cooperation between science, industry and ministries should be pursued in order to identify information gaps and potential disparities at an early stage and hence avoid them.

Medium-term / long-term prioritization of liquid sustainable fuels in aviation and shipping

As sustainable liquid fuels will most likely be limited, even in the longer term, it is essential to utilize the feedstocks and fuels in sectors or transport areas in which no alternatives exist for an extensive reduction of GHG emissions (e.g. through direct electrification or the direct use of hydrogen) in the medium to long term. This specifically applies to aviation as well as (deep-sea) shipping and, to some degree, to long-distance heavy-duty vehicles.

GHG reduction obligation for SAF in Europe

A wide variety of options are available for introducing a quota obligation model (mandate) foe SAF. One option is a GHG reduction obligation – as implemented in Germany for the promotion of biofuels. It is an effective instrument to promote SAF and reduce greenhouse gas emissions in aviation within an appropriate time-scale and in a predictable manner. At the same time, planning and investment security for the expansion of SAF production capacities can be provided, since a defined demand for SAF is generated over time.

A GHG reduction obligation in aviation would, for example, obligate fuel importers to reduce the average GHG emission balance of (fossil) aviation fuels that are supplied to the market by blending them with SAF, which has less GHG emissions. The amount of SAF required to meet this obligation depends on the respective (life cycle) emissions of the corresponding SAF option. To conclude, the better / the lower the emission balance of a SAF option, the less SAF is required to achieve the specified emission reduction, and vice versa.

Hence, within a GHG reduction obligation, also the (life cycle) emission balance of a SAF option (in conjunction with their production costs) serves as a benchmark, compared to pure blending mandates. This essentially promotes sustainable fuel options that allow for low GHG mitigation costs. In other words, they promote the most cost-effective GHG gas reduction option possible. The introduction of a GHG reduction obligation for SAF can thereby accelerate the achievement (by 2030) of a significant use of SAF – and thus a corresponding climate protection effect.

Quota obligation schemes which promote SAF on a national level have, in various European countries, already been adopted (legally or de facto) or are under discussion (e.g. Norway, Sweden, Finland, France, Spain, the Netherlands, the United Kingdom). For the purpose of inducing the greatest possible SAF demand through a quota obligation, a GHG reduction obligation for SAF should, on a European scale at the very least, be implemented as a matter of urgency. This could achieve the highest possible GHG reductions and cost degressions, through economies of scale, can optimally be exploited. This is particularly crucial so as to reduce competitive distortions whenever practicable, to generate the highest possible user acceptance, and to minimize or avoid any negative environmental secondary effects (e.g. tankering or re-routing). The implementation of an obligation should therefore be realized on a European or at least intra-European level. The latter would almost be compatible with the current scope of EU ETS for aviation.

A quota obligation scheme must additionally be in accordance with RED II and, above all, fulfill the predetermined sustainability criteria. It should be implemented as quickly as possible and gradually increase to a GHG reduction of at least 10 % by 2030; this is broadly in correspondence with the overall RED II target for the transport sector.[2] However, if aviation is to make an equivalent contribution to the climate targets for the German transport sector (climate gas reductions of 40 to 42 % compared to 1990 levels by 2030), an even significantly higher rate would be required if these GHG emission reductions are to be achieved by SAF (and not, for example, by reducing commercial air traffic overall). Until a quota obligation scheme is realized throughout the EU, Germany should follow the examples of other EU member states; a quota obligation scheme for SAF can be implemented effectively and simply on a German level in the context of the upcoming implementation of RED II into German law.

As there is a potentially limited feedstock availability for biofuel production and because of the projected strong market growth of aviation, electricity-based fuels will have to supplement biofuels in the medium term and possibly replace them altogether in the long term. Since great commercial PtL shares are not to be expected until after 2030 and the investment costs for setting up production of PtL fuels are comparatively high, a sub-mandate must ensure a minimum share of these fuels in the overall fuel mix; all within the framework of a GHG reduction obligation. In addition to supply-side PtL promotion, this also guarantees demand and implementation of such fuels. This further makes it possible to pass learning curves and thus potentially reduce the costs of PtL fuels in the long term. A PtL sub-mandate respective to domestic German air traffic could be introduced starting at 1 % from 2025 and increased by 1 percentage point each year until 2030. However, the introduction of an obligation / mandate as part of the German implementation of RED II must also consider the availability and efficient use of sustainable biofuels in addition to PtL kerosene. The proposed quota level of 0.5 % in 2026 and 2 % in 2030 should therefore be doubled at least in order to promote access to the German market for sustainable biokerosene as well.

SAF opt-in

In addition to the introduction of a SAF mandate, an opt-in mechanism can be used to further incentivize cost effective sustainable aviation fuels on the market and thus promote their use. This would permit existing biogenic SAF options the access to the market and allow to gain experience in terms of administrative and accounting related SAF processes.[3] Fuel producers, similar to those in the Netherlands, could for example, receive certain certificates

[2] According to Article 25(1) of RED II, the share of renewable energy in the final energy consumption of the transport sector of each member state must be at least 14 % by 2030. In addition, liquid fuels of non-biogenic origin must have a minimum GHG saving of 70 % according to Article 25(2). Thus, the 14 % in terms of energy content corresponds to a GHG reduction rate of about 10 %.

[3] A consistent administrative operation of sustainable aviation fuels through practicable verification and accounting procedures is not yet in place [Bullerdiek et al. 2019b; Pechstein et al. 2020].

through an opt-in mechanism for the production of certified sustainable aviation fuels, which they can sell to obligated parties in order to meet the road transport quota obligation. The produced SAF is then made available as "conventional" aviation fuel. For the corresponding SAF, a sustainability claim or the claim for accounting GHG emission reductions thus expires.

Supporting Measures

The following measures are intended to reduce and avoid current and future obstacles to the use of SAF and to support the previous measures in order to further pave the way for large-scale SAF usage.

Timely communication with (inter-)national NGOs and associations

The illustrated measures and their intended effects as well as their impacts on the environment and the population must be transparently and promptly in order to eliminate potential misunderstandings or take further argumentation and points of view in regard. National NGOs should therefore be involved in the discussions at the earliest possible time. In addition, national or transnational measures can only be a first step towards effective international measures to achieve a significant reduction of emissions in international aviation through the use of sustainable fuels. It is therefore equally important to communicate and discuss planned measures with international associations, not least with the aireg sister organization CAAFI in the USA.

Debate on the long-term role of biofuels

From an economic perspective and considering existing technologies and feedstock availability, a timely market introduction of sustainable aviation fuels can only happen on the basis of biogenic SAF. Biogenic fuels cannot serve as the only renewable fuel option in aviation and must be supplemented by other feedstock options, especially PtL fuels in the medium term and partially substituted in the long term. As part of a holistic strategy, it is necessary to evaluate the role of biogenic fuels. It must be discussed whether, when and how a specific biofuel option or technology should be pursued and promoted in the future alongside the commercialization of PtL. This for instance, applies to the feedstock option "municipal waste".

A short-term build-up of higher biofuel production capacities, which could potentially become obsolete with the development of future large-scale PtL plants, should be avoided from the beginning. This requires a targeted discussion of whether or which biofuel options should and must be promoted and made available, from when and to what extent.

Concepts for the verification and accounting of SAF / SAF meta-standard

The supply of feedstocks for SAF production and the availability of SAF options is likely to substantially vary regionally and continentally, especially during market ramp-up phases. As airlines operate on an international and intercontinental basis, they do not depend on the SAF offer in their home market exclusively as they can theoretically acquire SAF within their entire route network and thus partially exceed the limitations of a domestic SAF offer.

Large-scale production of SAF could, later in time, become more prevalent in certain areas and countries in which sufficient supply of feedstocks for biogenic and/or electricity-based SAF are provided, compared to other regions. Despite the existing international and intercontinental route network, the ability to acquire SAF is therefore likely to be (severely) restricted or unevenly distributed for certain airlines – and this regardless of the fact that there may be a willingness to pay or that the use of SAF is predetermined by regulatory measures (e.g. SAF mandates).

With the intention of increasing the global availability of SAF without having to rely on local, regional, national or continental feedstock supplies, available production pathways and plant capacities, logistics and supply chain or the route network of airlines, but to always be able to access a general/global SAF supply, suitable concepts for the verification, implementation and accounting of SAF must be established. A book-and-claim methodology (Fig. 12) is particularly suitable for this purpose, as it physically decouples SAF uptake and SAF use from the accounting of GHG emission reductions, thus creating an effective degrees of freedom in terms of SAF accounting [Pechstein et al. 2020]. This means that SAF can be produced and supplied to a market where it is most suitable due to the availability of feedstocks and production facilities, for example, and a cost-effective production and supply is possible. This also covers the fact that the impact of GHG emissions is a global effect and not (or only slightly) dependent on the location of the physical SAF use. This further provides maximum flexibility in the supply and implementation of SAF, potentially avoiding possible "unnecessary" fuel transports between production sites and distant airports or even intermediate storage.

Such concepts also serve, above all, to allow for a flexible and administratively simple verification and accounting of SAF in instruments such as the EU ETS or CORSIA. In principle, reporting requirements should ensure that users (airlines) can also have the emission reductions achieved by SAF credited to their company's carbon footprint.

Suitable reporting and accounting concepts and further required elements are to be examined. An example for this could be an international SAF meta-standard with international air traffic sustainability criteria, so that every airline can be assured, regardless of the point of departure, that an uplifted sustainable aviation fuel was produced sustainably in accordance with such a global standard.

Fig. 12 **Book & Claim accounting concept**

Development of niche markets for SAF

Especially at the beginning of a SAF ramp-up and in the absence of effective regulatory frameworks, it can be beneficial to foster the initial use of SAF in niches and gain further experience in operational deployment. This could include niches where there is potentially a higher willingness to pay (for fuel). This, for e.g., can be the general aviation sector, where an energy tax is also paid for the utilization of aviation fuels. SAF's competitive barriers can therefore be exceeded more easily (provided that there is no mandatory energy tax for SAF).

An additional incentive for SAF use could involve the government taking up a certain pioneering role and demonstrating the use of SAF in government flights. These and further niches could be activated for initial SAF uses. They, however, only represent a primary step and do not replace the necessity to establish a holistic and strategic regulatory framework for the long-term large-scale use of SAF.

Information center on regulatory frameworks of SAF

For start-ups and medium-sized companies, it is hardly feasible to understand and permanently follow the constantly changing legislation, especially regarding RED II, CORSIA and international or national standards, in sufficient detail. This creates a high degree of uncertainty as to whether (innovative) manufacturing processes will be recognized. In addition, the paths to recognition and admission are often unclear.

An information center should therefore be established, e.g. at a subordinate authority, higher education institution, that provides know-how and knowledge in a secure and packaged manner, giving clarity on whether and to what extent, or with which further measures, a fuel can be credited under certain regulatory frameworks (e.g. mandates under RED II, but also in steering instruments of other countries, e.g. the USA).

Development of marketing strategy and public relations for SAF market injection mechanism

A marketing strategy must be developed in order to not only inform both the public and concerned stakeholders in advance about the envisaged measures and their impacts but also to prevent miscommunication of the past, which for example occurred, with the introduction of biogenic fuels in road transport (e.g. E10 introduction). In this regard, the introduction of the presented GHG reduction obligation for aviation must also be strongly integrated into the public work relations of the corresponding stakeholders, NGOs and the relevant authorities so as to ensure a comprehensive acceptance in all sectors.

References

Agora, Frontier Economics Ltd. (2018): The Future Cost of Electricity-Based Synthetic Fuels. Agora Energiewende; Agora Verkehrswende; Frontier Economics Ltd. Berlin, Köln.

Airbus (2019): Global Market Forecast. 2019-2038. Cities, Airports & Aircraft. Airbus S.A.S. Toulouse.

aireg (2012): Klimafreundlicher fliegen: Zehn Prozent alternative Flugkraftstoffe bis 2025. Aviation Initiative for Renewable Energy in Germany e. V. (aireg). Berlin.

aireg (2020): Synthetische Luftfahrtkraftstoffe – eine aktuelle Bestandsaufnahme. Aviation Initiative for Renewable Energy in Germany e. V. (aireg).

Boeing (2019): Commercial Market Outlook. 2019–2038. The Boeing Company. Seattle.

Brynolf S, Taljegard M, Grahn M, Hansson J (2018): Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews. Rev 81: 1887–1905.

Bullerdiek N, Buse J, Dögnitz N, Feige A, Halling A-M, Hauschild S, Hawighorst P, Kaltschmitt M, Kuchling T, Kureti S, Majer S, Marquardt C, Müller-Langer F, Neuling U, Oehmichen K, Pechstein J, Posselt D, Scheuermann S, Schripp T, Stein H, Zschocke A (2019a): Einsatz von Multiblend-JET-A-1 in der Praxis. Zusammenfassung der Ergebnisse aus dem Modellvorhaben der Mobilitäts- und Kraftstoffstrategie. Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ). Leipzig.

Bullerdiek N, Buse J, Kaltschmitt M, Pechstein J (2019b): Regulatory Requirements for Production, Blending, Logistics, Storage, Aircraft Refuelling, Sustainability Certification and Accounting of Sustainable Aviation Fuels (SAF). Report within the Research and Demonstration Project on the Use of Renewable Kerosene at Airport Leipzig / Halle (DEMO-SPK). Adeptus Green Management GmbH; Institut für Umwelttechnik und Energiewirtschaft (IUE). Hamburg.

CST (2020): Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation. Insight Report. Clean Skies for Tomorrow (CST); McKinsey & Company; World Economic Forum (WEF).

Dietrich S, Zech K, Oehmichen K, Müller-Langer F, Majer S, Kalcher J, Naumann K, Wirkner R, Pujan R, Braune M, Gröngröft A, Albrecht U, Raksha T, Weindorf W, Reichmuth M, Gansler J, Schiffler A (2017): Machbarkeitsanalyse für eine PTG-HEFA-Hybridraffinerie in Deutschland. Im Auftrag des Bundesministeriums für Verkehr und digitale Infrastruktur (BMVI) im Rahmen der Mobilitäts- und Kraftstoffstrategie der Bundesregierung (MKS). Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ); Ludwig-Bölkow-Systemtechnik GmbH (LBST); Leipziger Institut für Energie GmbH (IE-Leipzig). Leipzig.

DLR, BDLI (2020): Zero Emission Aviation – Emissionsfreie Luftfahrt. White Paper der deutschen Luftfahrtforschung. Deutsches Zentrum für Luft- und Raumfahrt (DLR); Bundesverband der Deutschen Luft- und Raumfahrtindustrie e.V. (BDLI). Köln.

EASA (2020): European Aviation Environmental Report. Sustainable Aviation Fuels. Figures and Tables. European Union Aviation Safety Agency (EASA). Online verfügbar unter https://www.easa.europa.eu/eaer/topics/sustainable-aviation-fuels/figures-and-tables, zuletzt aktualisiert am 20.10.2020, zuletzt geprüft am 20.10.2020.

EC (2020a): ReFuelEU Aviation Public Consultation. European Commission (EC). Brüssel. Online verfügbar unter https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12303-ReFuelEU-Aviation-Sustainable-Aviation-Fuels/public-consultation, zuletzt aktualisiert am 23.11.2020, zuletzt geprüft am 24.11.2020.

EC (2020b): SAF Roundtable n°2. ReFuelEU Aviation. European Commission (EC).

EEX (2019): EEX Market Data. EUA Primary Auction Reports. European Energy Exchange (EEX). Leipzig. Online verfügbar unter https://www.eex.com/en/market-data/environmental-markets/auction-market/european-emission-allowances-auction/european-emission-allowances-auction-download, zuletzt geprüft am 23.10.2019.

EIA (2020): International Energy Data. Jet fuel consumption. U.S. Energy Information Administration (EIA). Online verfügbar unter https://www.eia.gov/opendata/qb.php?category=2135044, zuletzt geprüft am 30.11.2020.

Hobohm J, Maur A auf der, Dambeck H, Kemmler A, Koziel S, Kreidelmeyer S, Piégsa A, Wendring P, Meyer B, Apfelbacher A, Dotzauer M, Zech K (2018): Status und Perspektiven flüssiger Energieträger in der Energiewende. Endbericht. Prognos AG; Das Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT; Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ). Basel.

IATA (2018): Fact Sheet. Climate Change & CORSIA. International Air Transport Association (IATA). Montréal.

IATA (2020a): Air Passenger Forecasts 2019-2039. International Air Transport Association (IATA). Montréal. Online verfügbar unter https://www.iata.org/contentassets/e938e150c0f547449c1093239597cc18/pax-forecast-infographic-2020-final.pdf, zuletzt geprüft am 15.10.2020.

IATA (2020b): Industry Statistics. Fact Sheet. June 2020. International Air Transport Association (IATA). Montréal.

IATA (2020c): Economic Performance of the Airline Industry 2020. Mid-year report. International Air Transport Association (IATA). Montréal.

ICAO (2017): Sustainable Aviation Fuels Guide. International Civil Aviation Organization (ICAO). Montréal.

ICAO (2018): ICAO Long-Term Traffic Forecasts. Passenger and Cargo. International Civil Aviation Organization (ICAO). Montréal.

ICAO (2019): CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. ICAO document. International Civil Aviation Organization (ICAO). Montréal.

ICAO (2020): ICAO Council agrees to the safeguard adjustment for CORSIA in light of COVID-19 pandemic. International Civil Aviation Organization (ICAO). Montréal. Online verfügbar unter https://www.icao.int/Newsroom/Pages/ICAO-Council-agrees-to-the-safeguard-adjustment-for-CORSIA-in-light-of-COVID19-pandemic.aspx, zuletzt aktualisiert am 15.10.2020, zuletzt geprüft am 15.10.2020.

IEA (2020): Changes in transport behaviour during the Covid-19 crisis. International Energy Agency (IEA). Paris. Online verfügbar unter https://www.iea.org/articles/changes-in-transport-behaviour-during-the-covid-19-crisis, zuletzt aktualisiert am 06.10.2020, zuletzt geprüft am 06.10.2020.

Jong S de, Hoefnagels R, Faaji A, Slade R, Mawhood R, Junginger H Martin (2015): The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison (6).

U Neuling (2019): Biokerosinherstellung. Verfahrensidentifikation, Simulation und Bewertung. 1. Auflage. Hamburg: Kovac, Dr. Verlag (Schriftenreihe Technische Forschungsergebnisse, 34).

Pavlenko N, Searle S, Christensen A (2019): The cost of supporting alternative jet fuels in the European Union. International Council on Clean Transportation (ICCT). Wilmington, zuletzt geprüft am 15.05.2019.

Pechstein J, Bullerdiek N, Kaltschmitt M (2020): A "book and Claim"-Approach to account for sustainable aviation fuels in the EU-ETS – Development of a basic concept. Energy Policy 136, S. 111014. DOI: 10.1016/j.enpol.2019.111014.

Schmidt P, Weindorf W, Roth A, Batteiger V, Riegel F (2016): Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Hg. v. Umweltbundesamt (UBA). Ludwig-Bölkow-Systemtechnik GmbH (LBST); Bauhaus Luftfahrt e.V. Dessau-Roßlau.

Thomson R, Sachdeva N, Healy A, Bailly N, Stern C (2020a): Sustainable Aviation Fuels. The Best Solution to Large Sustainable Aircraft. Roland Berger. London.

Thomson R, Weichenhain U, Sachdeva N, Kaufmann M (2020b): Hydrogen: A future fuel for aviation? Roland Berger. München.

Timmerberg S, Bullerdiek N, Kaltschmitt M, Gnann T, Neumann F, Wietschel M (2019): Teilstudie „Import von Stromkraftstoffen für den Verkehr – Lkw, Binnen-/Seeschiffe, Flugzeuge". Wissenschaftliche Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie. Institut für Umwelttechnik und Energiewirtschaft (IUE); Fraunhofer ISI. Hamburg.

WEF (2020): Joint Policy Proposal to Accelerate the Deployment of Sustainable Aviation Fuels in Europe. A Clean Skies for Tomorrow Publication. White Paper. World Economic Forum (WEF). Köln, Genf.

World Bank (2020): Air Transport. Passengers Carried. World Bank. Washington D.C. Online verfügbar unter https://data.worldbank.org/indicator/is.air.psgr, zuletzt geprüft am 25.03.2020.

Members of aireg

AIRBUS

air bp

Aviation Fuel Projects Consulting GmbH & Co. KG

BAUER RESOURCES

Bauhaus Luftfahrt Neue Wege.

Hamburg | Behörde für Wirtschaft und Innovation

Catalysis Leibniz-Institut für Katalyse e.V.

CAPHENIA Turning CO_2 into fuel

Deutsche Post DHL Group

Die Senatorin für Wirtschaft, Arbeit und Europa

DLR Deutsches Zentrum für Luft- und Raumfahrt

Fraunhofer IBP

Global Bioenergies

GRIESEMANN GRUPPE

HESSEN Hessisches Ministerium für Wirtschaft, Energie, Verkehr und Wohnen

MTU Aero Engines

ISCC International Sustainability & Carbon Certification

JatroGreen Sustainable Energy Madagascar

JÜLICH Forschungszentrum

KIT Karlsruhe Institute of Technology

NESTE

Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz

OMV

PETRIXO OIL & GAS

reisetopia

ROSNEFT DEUTSCHLAND

SH Schleswig-Holstein Ministerium für Wirtschaft, Arbeit, Verkehr und Technologie

sunfire®

Institut für Umwelttechnik und Energiewirtschaft IUE

TOTAL

WIWeB