ANALYSIS

Defossilising aviation with e-SAF

An introduction to technologies, policies, and markets for sustainable aviation fuels

Imprint

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Foreword

Dear readers,

What began as a humble experiment with a cotton-clad airframe at Kitty Hawk a century ago has morphed into a trillion-dollar industry that fulfils a crucial role in our highly globalized world. To be sure, aviation is much more than a means of transport. It brings the world closer together in very direct sense, enabling cooperation and exchange between peoples. Yet not all of aviation's effects are salubrious. Aviation sector emissions have been on an upward trajectory for decades – and are anticipated to grow even further in coming years, despite increases in aircraft efficiency.

The phasing out of fossil fuels in the aviation sector represents a major challenge in the broader project to achieve climate neutrality. One important option is a modal shift to emissions-free and more energy efficient mobility solutions, but the demand for flying will remain significant nevertheless. And, like maritime shipping, aviation is a "hard-to-abate" sector, as there are significant technical impediments to direct electrification and hydrogen-based propulsion. Together, aviation and shipping account for some 5 percent of the global CO_2 emissions – and this share is likely to increase as other sectors defossilise.

How can we move closer to climate-neutral aviation without sacrificing the benefits that aviation brings in our globalized world? In a rare instance of unanimity, policymakers, academics, and business leaders believe that climate-neutral aviation is only possible over the long term given the replacement of conventional jet fuel with more sustainable and climate friendly alternatives. Sustainable aviation fuels (SAF) come in various forms, from biofuels to synthetic e-SAF. Nevertheless, global production quantities have been expanding at a very slow pace.

Given the drawbacks and technical limitations associated with specific e-SAF production routes, experts see the large-scale global production of e-SAF from renewable electricity and atmospheric CO_2 as the most promising option for carbon-neutral aviation. However, e-SAF production at a sufficient scale would necessitate a massive increase in global renewables generation as well as significant additional R&D and investment in direct air capture (DAC) technology. It would also consume large volumes of fresh water, which, particularly in arid regions with advantageous conditions for solar PV, would entail the need for large-scale water desalinization.

Accordingly, the challenges are significant. However, countries that commit themselves to developing e-SAF production to serve global sustainable aviation fuel demand could reap significant economic rewards, not only in terms of favourable balance-of-trade impacts but also knock-on effects for domestic economic development. Yet as "sweet spot" regions for e-SAF production move to take advantage of this development opportunity, efforts must be made to ensure that associated investment does not cannibalize domestic energy-transition efforts, is guided by consistent sustainability criteria, and does not run roughshod over principles of just and inclusive economic development.

This paper provides an overview of the current state of research with a view to the defossilisation of the aviation sector using e-SAF. It is closely related to our discussion paper "E-fuels: Separating the substance from the hype", in which we outlined how electricity-based synthetic fuels can contribute generally to the energy transition in transport. The key takeaways offered by both papers are similar. However, in this paper we focus strictly on aviation, discussing in detail the potential offered by e-SAF.

Our goal is to furnish an evidence-based foundation for policy debate while illuminating options for just and inclusive development. If policymakers wish to ramp up global e-SAF production and thus enable the defossilisation of aviation, then associated decisions must be made in the near term based on an internationally concerted strategy that is informed by clear priorities. To this end, it is crucial to distinguish between viable options and mere wishful thinking.

We hope you find this paper both useful and informative.
Best regards,

Wiebke Zimmer and Torsten Schwab
Deputy Executive Director, Director
On behalf of the Agora Verkehrswende and International PtX Hub Team

Berlin, July 2024

Key takeaways

1 **The current system of fossil fuels is not a viable option for the future, and SAF will be indispensable for advancing climate protection in aviation.** The goal of transitioning the aviation sector to battery electric, hydrogen electric, and/or hydrogen combustion systems faces major technical challenges, necessitating a reliance on liquid hydrocarbons for many years to come, particularly when it comes to long haul flights or the decarbonization of existing aircraft. While progress in reducing aviation sector emissions can be achieved through technical innovations and operational improvements, remaining hydrocarbon fuel demand will have to be covered with e-SAF, which offers the advantage of nearly unlimited scalability. The major task in the coming years will be to advance learning curves and exploit economies of scale in order to realize the greatest possible reductions in e-SAF production costs.

2 **Policymakers across the globe should facilitate a market ramp-up of e-SAF by adopting suitable political and regulatory frameworks.** Far from relying on individual measures, policymakers should strive to adopt comprehensive regulatory packages that target actors throughout the fuel supply chain. The coordinated introduction of such measures in numerous countries would help to reduce the risk of market fragmentation and carbon leakage. Accordingly, international cooperation on e-fuel investment and regulatory policy is essential.

3 **The development of comprehensive sustainability criteria for e-SAF – and not just for hydrogen – is essential for their socially and environmentally sound production and use.** The following principles should apply to international cooperation, standards, and certification systems: (1) The supply of renewable electricity to the domestic economy and population should have priority over the production of e-fuels for export; (2) e-SAF projects should rely exclusively on additional renewable energy capacity that is developed as a supplement to domestic renewable needs; (3) such supplemental capacity should be developed in a manner that supports local infrastructure expansion and economic development; and (4) renewable electricity should be used as efficiently as possible in e-fuel production countries, with priority given to direct electric applications, such as electric vehicles.

4 **Once the political frameworks for e-SAF are in place, it will fall to industry and investors to rapidly expand the supply of e-SAF.** Projected global e-SAF production in 2030 correspond to around 3% of the EU's current jet fuel demand. Accordingly, for the meaningful decarbonization of aviation, it is necessary not only to realize currently announced projects but also significantly expand the number of projects (both large and small) in the development pipeline. In the area of carbon sourcing, additional R&D is needed to improve technological solutions (including in particular direct air capture, or DAC) and enable widespread adoption.

5 **A sole focus on "sweet spot" regions that offer particularly beneficial conditions for e-SAF production is insufficient; rather, an overarching strategy that addresses all major dimensions of e-SAF production is needed.** An effective strategy for ramping up e-SAF production must ensure ample renewables generation, the sustainable sourcing of carbon, and viable models for project financing. Policymakers must also devote attention to steering the production and use of e-SAF in a manner that serves climate policy goals. The establishment of robust international standards will play an important role in this regard.

Contents

1 | Introduction: Aviation in a global context

International aviation is responsible for about 3% of global CO_2 emissions. However, its actual impact on the climate is likely to be significantly larger. In addition to direct CO_2 emissions from the combustion of fossil jet fuels and the emission of other greenhouse gases in fuel production and supply, there are also other "non-CO_2" effects that impact the earth's energy balance, including contrails and the resulting contrail cirrus clouds. Furthermore, air traffic has been growing steadily in recent decades, despite a temporary slump triggered by the global pandemic. The total climate impact of aviation is thus on the rise, even as aircraft have become more efficient.

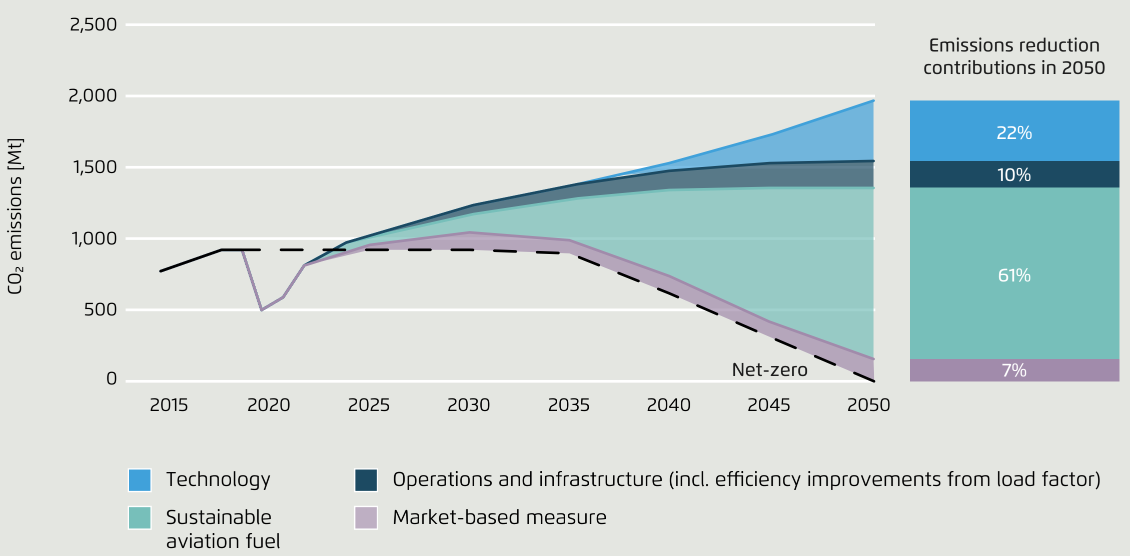
The aviation sector must significantly reduce its climate impact to be in alignment with the 1.5°C target. In recognition of this fact, the Air Transport Action Group (ATAG) and other aviation associations have set the goal of achieving carbon-neutral growth from 2025 onwards and of achieving net-zero CO_2 emissions by 2050 (Figure 1).

However, the phasing out of fossil fuels – also known as defossilisation – is confronted by unique challenges in the aviation sector. These challenges include in particular the long service life of aircraft (20–30 years) and the special requirements placed on aviation fuels (including their energy density, flash point, and cold flow specifications). While work is underway to develop battery electric and hydrogen powered aircraft that would reduce the need for liquid hydrocarbon fuels, for the foreseeable future, air traffic will continue to rely on liquid fuels, particularly when it comes to long-haul flights.

Accordingly, greater climate efficiency in the aviation sector is being pursued through various means, including technical innovations (e. g. lightweight construction, more fuel-efficient propulsion), improved operational measures (e. g. optimized flight routes and cruising altitudes) and, last but not least, reliance on sustainable aviation fuels (SAF) – that is, substitute fuels that are as sustainable and climate-friendly as possible. Figure 2 provides an overview of propulsion options in relation to flight distances and climate impacts.[1]

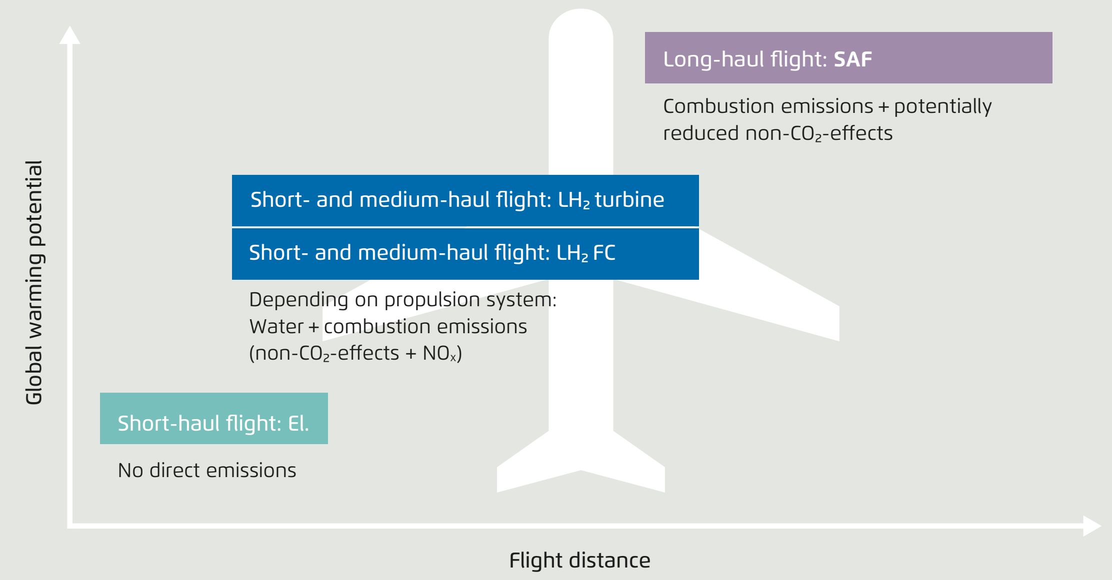
1 BDLI (2020), DLR (2020), T&E (2022a).

Options for achieving the emission reduction goals of the international aviation industry Figure 1



Agora Verkehrswende and International PtX Hub (2024) | Note: According to the ATAG Waypoint 2050 Scenario 1 (pushing technology and operation). Source: ATAG (2021).

Propulsion and energy transition options for aviation and their climate impacts — Figure 2



Agora Verkehrswende and International PtX Hub (2024) | Note: El. = Electric, FC = Fuel cell, LH2 = Liquid hydrogen, SAF = Sustainable aviation fuel.

Non-CO_2 effects

Reliance on carbon-neutral and nearly carbon-neutral SAF reduces the climate impact of aviation, since no additional fossil CO_2 is emitted. However, due to "non-CO_2 effects" the actual climate impact of aviation is significantly higher than the direct emissons from fuel combustion. The term "non-CO_2 effects" refers to various atmospheric impacts, including aircraft condensation trails, which can promote heat-trapping cirrus cloud formation, and nitrogen oxide (NO_X) emissions, which can lead to the formation of ozone, a potent greenhouse gas (see Figure 3). While some non-CO_2 effects tend to reduce global warming, the net warming impacts are at least as high as aviation's carbon emissions. According to current estimates, non-CO_2 effects – which, at least in part, are caused by any hydrocarbon fuel – represent up to two-thirds of aviation's total climate impact.[2] Such effects may even occur when aircraft are fully powered by hydrogen, although the associated climate impacts are even more uncertain in this case.[3] In any event, non-CO_2 impacts are currently not being taken into account, neither in international aviation's carbon-neutrality targets, nor in CO_2 trading schemes.[4] There are various strategies for reducing non-CO_2 effects. The specific composition of aviation fuel influences contrail properties and can reduce the risk of cirrus cloud formation. Synthetic fuels such as e-SAF have high purity levels, which results in fewer particulate emissions, thus reducing the likelihood of cirrus cloud formation.[5]

2 DLR (2024), Lee et al. (2021).

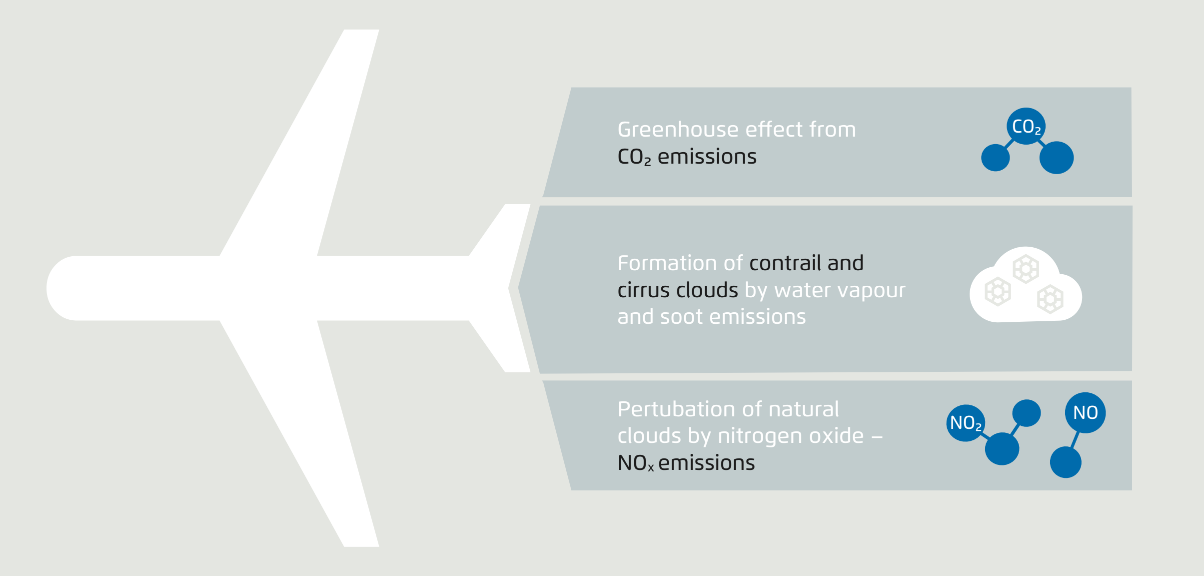
3 Airbus (2023a).

4 However, the revised EU ETS (see section 6) does at least speak to this issue, noting an "MRV framework for non-CO_2 emissions from aviation must be implemented from 2025 and evaluated in 2027. In 2028, following an impact assessment the Commission can put forward a proposal to address non-CO_2 emissions from aviation" (European Parliament 2024).

5 T&E (2022b).

The climate impact of non-CO_2 effects

Figure 3



Agora Verkehrswende and International PtX Hub (2024) | Source: Climaviation (2024).

1.1 Climate mitigation in aviation

Aside from measures pursued within the aviation sector itself, there are various options for reducing the overall climate impact of aviation, including policies to encourage a mobility shift (e. g. increased reliance on high-speed rail); carbon pricing systems (e. g. inclusion of aviation in the EU ETS); and demand reduction measures (such as business travel restrictions). If demand management policies were combined in a way that ensures maximum impact, European aviation emissions could be cut roughly in half, a study conducted by T&E has found.[6]

However, such policy scenarios for reducing aviation emissions are unlikely to be achieved on a global scale, especially when emerging regions are considered. Accordingly, it is necessary to consider measures that can be taken to reduce the climate impact of aviation but which do not necessitate comprehensive national legislation. As a first step, one should encourage the aviation industry to implement efficiency measures that reduce the amount of fuel burned per passenger kilometer, thereby reducing GHG emissions. There are two ways to increase efficiency: (1) technical innovation; and (2) the optimization of flight and ground operations. Regardless of any commitment to environmental protection, airlines have a considerable economic incentive to implement such measures, as they reduce fuel consumption, which has a strong impact on their profitability.

Technical Innovation

Efficiency-minded technical innovations aim to directly reduce the specific fuel consumption of aircraft by various means (e. g. reducing weight, improving aerodynamics, and improving the efficiency of propulsion systems). While “disruptive” aircraft designs such as truss-braced wing and wing-body concepts have been discussed for decades, serial production of these aircraft types has yet to take place, not least due to high development costs and the need for new production technologies. Additional hurdles to the adoption of radical new designs include the need to adapt airport infrastructure (boarding bridges, runways) and the rigorous certification process that would necessarily precede widespread commercial use.

Aircraft manufacturers have been working to reduce the weight of new aircraft generations, not only through improved manufacturing techniques, but also through a

6 T&E (2022a).

reliance on lighter composite materials that can replace metals (particularly aluminum). Design and production innovations such as 3D printing will enable airframe weight to be further reduced in coming years. Promising potential is also seen in the area of integrated structures and components, which can reduce the total number of parts required, and, by extension, total weight.[7]

Another means of reducing fuel consumption is to improve aircraft aerodynamics. Important technical options in this regard include variable wing camber, wingtip devices, and adapted surfaces to reduce drag (e. g. riblets, supercritical airfoils, sharkskin technology). While some of these features have to be implemented during the initial design process, others can be added to existing aircraft. Adaptive wings that adjust their shape according to changing flight conditions in order to optimize lift and reduce fuel consumption represent one area of cutting-edge development.

Significant reductions in fuel consumption can also be achieved with more fuel-efficient propulsion systems (Figure 4). By way of example, the Airbus A320neo is 10–20% more efficient that the A320, its predecessor model, thanks to improved engine technology. However, fuel efficiency gains of just 5–10% are anticipated for the next generation of turbofan engines from 2030 onwards, due to limited potential for futher optimization.[8] According, engineers have been exploring open-rotor and turboprop engine designs, which could allow efficiency gains of up 20–30% over current turbofan engines.[9] While large efficiency improvements can be achieved when a technology is new, the law of diminishing returns invariably applies when it comes to new designs.

Optimization of flight and ground operations

The emissions reductions that can be achieved through the optimization of ground and flight operations are often subsumed under the category of "operational measures", although the two are quite distinct. The major point of difference relates to who implements the associated measures: airlines and air-traffic control agencies are responsible for improving flight operations, while airport operators and ground-support equipment manufacturers are responsible for improving ground operations.

The optimization of ground operations encompasses a range of measures, from the adoption of zero emission ground support equipment to the retrofitting of parking positions with electrical power supply to reduce emissions from aircraft APUs (auxiliary power units). The optimization of ground operations also extends to the enhancement of overall airport infrastructure (including building weatherization and increased reliance on renewable electricity). Various airports worldwide have also been adopting electric and hydrogen-fuel-cell vehicles for ground logistics (such as tugs, tractors, and belt loaders). As a complement to such measures, airports have been installing on-site wind and PV systems. Delta Airlines has been a frontrunner in this area, boasting nearly 100% electric ground support equipment at its hubs in Salt Lake City and Boston.[10] Such measures not only contribute to climate mitigation in the aviation industry, but also reduce other harmful local emissions such as particulate matter, NO_X, SO_X and even noise. However, it is important to keep in mind that emissions from ground operations are not normally considered when calculating the climate impact of aviation.

The optimization of flight operations, by contrast, mainly pertains to optimized speed and altitude management as well as improved routing in order to reduce fuel consumption, and, by extension, the climate impact of aviation. Optimized air traffic control (as foreseen e. g. by the Single European Sky initiative[11]) and other operational measures could achieve cumulative emission reductions of approximately 5%, according to a 2021 study.[12] Additional minor efficiency gains could also be achieved by increasing the load factor (i. e. the number of passengers per flight) and aircraft size. The Air Transport Action Group (ATAG) has estimated an emissons reduction potential of between 0 and 6 percent up to 2050 based on improved flight operations.[13]

7 Airbus (2021).

8 IATA (2019).

9 Safran (2019). IATA (2019), by contrast, only sees efficiency improvement potential of 5–10% for such engine types.

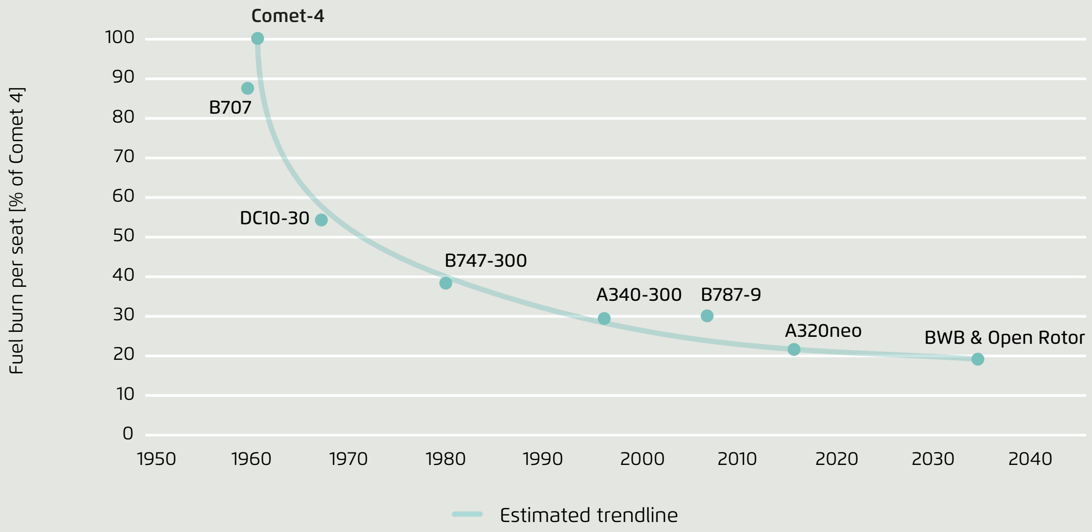
10 Delta (2023).

11 Single European Sky is a European Commission initiative that aims to combine the mostly national air traffic control jurisdictions into a larger and thus more optimized combined control zone, which would allow air space to be used more efficiently. Although the merging of air traffic jurisdictions has been discussed at the EU level since 1999, it has not yet to be implemented, mainly due to the security and sovereignty concerns of some Member States.

12 Royal NLR, SEO Amsterdam Economics (2021).

13 ATAG (2021).

Energy efficiency gains in new jet turbine generations are gradually diminishing over time Figure 4



Agora Verkehrswende and International PtX Hub (2024) | Note: Fuel burn or energy consumption per seat of different aircraft compared to the Comet-4 (first commercial jet-powered aircraft). Source: IATA (2023).

However, these and other efficiency improvements will most likely be outpaced by growth in demand for air transport (see also Figure 5). To be sure, efficiency measures can never fully eliminate emissions. Accordingly, the use of renewable energy carriers is necessary to come anywhere close to net-zero emissions in aviation. Until technological advancements enable serial production of hydrogen- and battery-powered aircraft, the shift away from conventional fuels in aviation will have to be achieved by running conventional jet engines on sustainable alternative fuels (SAFs).

1.2 Overview on aviation fuels

The aviation sector relies on various fuel types, as defined by international standards (such as those issued by ASTM International). The most widely used fuel types are:

- Jet fuel (Jet A, Jet A-1, Jet-8)
- Kerosene naphtha mixture (Jet B)
- Aviation gasoline (Avgas)
- Sustainable aviation fuels (SAF)

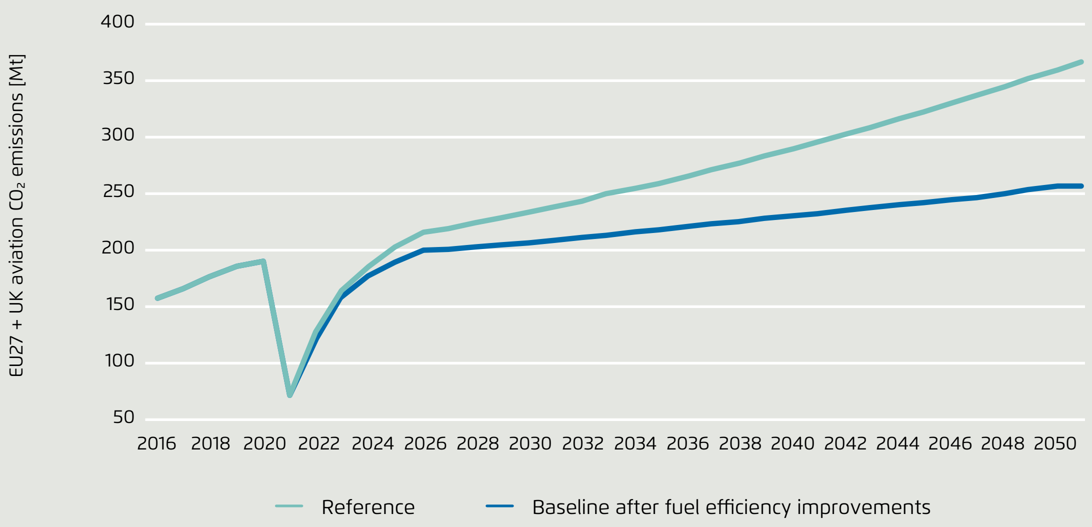
Jet fuel

ASTM D1655 was adopted in 1959, thus establishing the Jet A-1 fuel standard. This standard, which is based on DEFSTAN 91 (the UK standard for jet fuels), applies to most of the world. Russia, China, India, and Brazil each have their own standards, but these primarily represent national implementations of ASTM D1655. In general, Jet A-1 is a refined light petroleum product (kerosene) with very specific characteristics (e. g. regarding its flash and freezing points). The main difference between Jet A (only used in the US) and A-1 (rest of the world) is the freezing point (Jet A freezes at -40°C; Jet A-1 at -47°C). After refining, various additives are mixed into the fuel to adjust its properties. The NATO military grade Jet Propellant 8 (JP-8) is based on Jet A-1, but contains even more additives.

Jet B

In very cold regions, a naphtha–kerosene mixture called Jet B is used, due to its very good cold-weather performance. Thanks to the high naphtha/gasoline share of roughly 7:10, it has a low flash point and a very low freeze point of 60°C. However, this makes it more dangerous to handle than Jet A-1, so it is only used in very cold climates (and mainly for military purposes).

CO_2 emissions reduction potential from fuel efficiency improvements in EU27 and UK aviation Figure 5



Agora Verkehrswende and International PtX Hub (2024) | Source: T&E (2022a).

AVgas
Smaller sport and private aircraft are often propelled by piston engines, demanding another fuel type. Aviation gasoline, or AVgas for short, is a high-octane leaded fuel. However, global demand for this fuel type is very low when compared to Jet A-1 or vehicle gasoline. Furthermore, as AVgas is usually more expensive than kerosene-based jet fuels, consumption levels have been declining in recent years.

Bio-SAF
Biofuels for aviation fall under the broader category of sustainable aviation fuels (SAF). Other common names include biojet, biokerosene, and biobased jet fuel. To be used in commercial aviation, these biofuels have to be produced using certified production processes and specific feedstocks (as defined by the ASTM D7566 standard; see below). The fuel produced in this manner is referred to as a synthetic blending component (SBC) and can be mixed with conventional Jet A-1 up to certain blending ratios, depending on the production process (see below). In contrast to other synthetic aviation fuels (such as e-SAF), the energy content of the final fuel and the carbon it contains originate from the biomass used as a feedstock.

e-SAF
Another SAF option is to synthesize fuel using electrical energy. The fuel synthesis process resembles that of bio-SAF, but electrolytic hydrogen and carbon dioxide serve as feedstocks. The production process must be certified under existing standards (such as ASTM D7566; see below) for admixture with conventional jet fuel and use in commercial aviation. Although the carbon used to synthesize e-fuels may stem from biogenic sources, the main difference to bio-SAF or biofuels is that the energy content results from the hydrogen. If this hydrogen is produced via electrolysis, the main energy content thus originates from electricity. In the broader discussion, many different terms are used to refer to these fuels, including e-fuels, e-kerosene, e-jetfuel, and PtL-SAF. However, in the context of this publication, only the term e-SAF is used.

2 | Sustainable Aviation Fuels

Due to the special requirements that aviation fuels must fulfil, including those related to safety, new fuels are subject to a complex approval process. This process is defined under the ASTM D4054 standard. The most widely used fuel type in civil aviation is Jet A-1, which is generally a petroleum product.[14] However, Jet A-1 can also include a synthetic blending component up to the blending limit defined by ASTM D7566. The resulting fuel blend must fulfill the overall specifications defined by ASTM D1655 (see below).[15] The blending components can be produced synthetically from coal or natural gas. Alternatively, they can be derived from biomass (bio-SAF) or hydrogen and CO_2 (e-SAF). Such blends are referred to as "drop-in fuels", because they are compatible with existing technical systems and infrastructure. In order to exploit the emissions reduction potential offered by such renewable fuels, the use of 100% SAF as an alternative to Jet A-1 is being discussed in the aviation sector. Complete Jet A-1 substitution will most likely be possible in the near future in connection with some SAF production routes.

14 Defined within ASTM D1655 – Standard Specification for Aviation Turbine Fuels.

15 Defined within ASTM D7566 – Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons.

2.1 Aviation fuel properties

ASTM approval requires adherence to a variety of specifications. Some of the most important chemical and physical fuel parameters with very strict thresholds are:

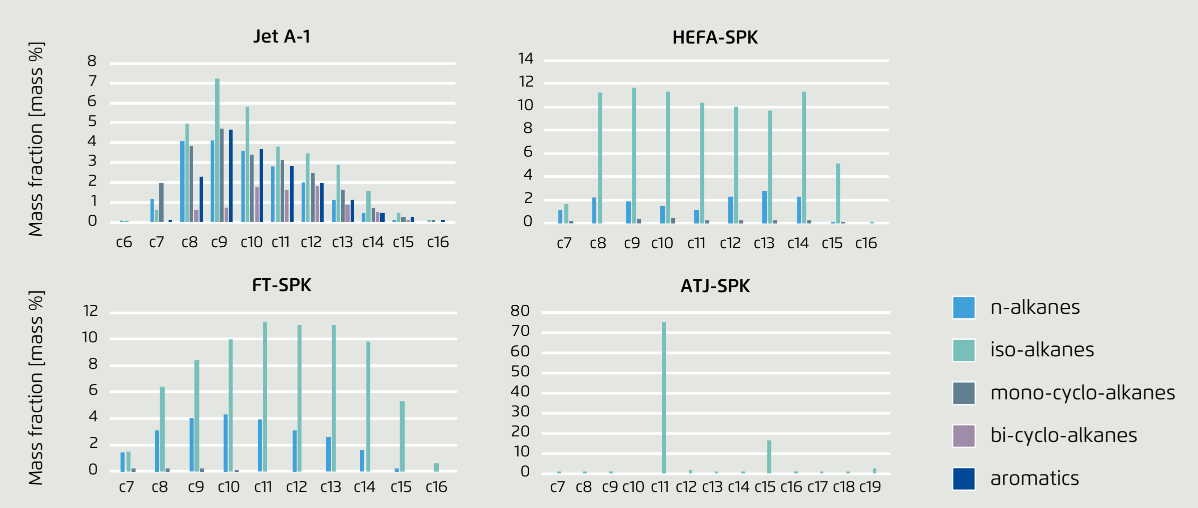
- Density
- Flash point
- Freezing point
- Heat of combustion
- Volumetric share of aromatics

These properties are often related to or influenced by additional properties not directly tested during certification. In addition to their impact on engine design and flight operations, these properties are relevant for ground handling and fuel system engineering (e.g. tank safety systems, heat exchangers, fuel pumps).

The defined specifications are of course met by conventional Jet A-1, as this represents the global standard for safe and reliable aircraft operation. However, the various specifications and thresholds can also be meet with various fuel formulas that are based on alternative production processes. Figure 6 shows the major hydrocarbon groups for approved SAF options, (as described in the next section below).

Comparison of different SAFs produced via approved production routes as well as experimental results for two new fuel candidates

Figure 6



Agora Verkehrswende and International PtX Hub (2024) | Source: P. Le Clercq, personal communication, June 18, 2024.

While the SAF types shown in Figure 6 exhibit divergent hydrocarbon profiles, some broad similarities exist, particularly with regard to the prevalence of some hydrocarbon groups (including alkenes and oxygenates). R&D in the domain of fuel design remains ongoing. Generally, the goal of such R&D is to create optimized fuel types that fulfill all specifications yet also show improved combustion properties as well as environmental or economic advantages.

2.2 Approved SAF production routes

Due to the high safety standards in aviation, every process that is used to produce SAF has to be certified by the international standards organization ASTM International. Usually, a production route is certified in combination with the applicable resources, e. g. different types of biomass. The process for approving a new SAF production route (as described in ASTM D4054) is cost and time intensive; it usually takes several years and may consume a large quantity of fuel (e. g. up to 100,000 litres). Recently a quicker and less intensive procedure was added to the ASTM standard, called the Clearinghouse method.[16] In addition, ASTM has implemented a fast-track process with reduced testing requirements, but only for blending ratios up to ten percent.[17]

To date, ten different processes have been approved: specifically, eight stand-alone processes under ASTM D7566,

16 ASCENT (2023).
17 Rumizen (2021).

Approved SAF production processes according to ASTM D7566 and D1655 as of March 2024 — Table 1

ASTM	Annex	Approval	Product / Process	Max. Blending Ratio	Main Intermediate Product	Resource Basis	(Potentially) e-SAF compatible
D7566	1	2009	FT-SPK	50 vol%	Syngas	LC, $H2+CO_2$	Yes
	2	2011	HEFA-SPK	50 vol%	Lipids (Prerefined)	Animal Fats, Veg. Oils	No
	3	2014	HFS-SIP	10 vol%	Sugar	Sugar, Starch, LC	No
	4	2015	FT-SPK/A	50 vol%	Syngas	LC, $H2+CO_2$	Yes
	5	2016	AtJ-SPK	50 vol%	Alcohol (Ethanol, Isobutanol, and Isobutene)	Sugar, Starch, LC	No [a]
	6	2020	CH-SK	50 vol%	Lipids (Prerefined)	Animal Fats, Veg. Oils	No
	7	2020	HC-HEFA-SPK	10 vol%	Algae Oil (Prerefined)	Algae	No
	8	2023	AtJ-SKA	50 vol%	Alcohol (Ethanol to Pentanol)	Sugar, Starch, LC	No
D1655	1	2018	Co-Processing	5 vol%	Lipids (Prerefined)	Animal Fats, Veg. Oils	No
	1	2020	Co-Processing	5 vol%	FT Syncrude	LC, $H2+CO_2$	Yes

A: Aromatics; ATJ: Alcohol-to-Jet; CH: Catalytic Hydrothermolysis; FT: Fischer–Tropsch; HC: Hydrocarbons; HEFA: Hydroprocessed Esters and Fatty Acids; HFS: Hydroprocessed Fermented Sugars; LC: Lignocellulose; SIP: Synthetic Isoparaffins; SK: Synthesized Kerosene; SKA: Synthesized Kerosene with Aromatics; SPK: Synthetic Paraffinic Kerosene

a Although e-SAF production from methanol technically can be seen as AtJ process, the production process as well as the final fuel properties will most likely vary from the currently approved AtJ routes and thus will most likely be approved within a new Annex.

Agora Verkehrswende (2024)

and two co-refining processes under ASTM D1655 (Table 1).[18] Additional production processes are currently being evaluated for ASTM D4054 approval – and further processes are under development, but have not yet begun formal qualification.[19] The Fischer–Tropsch process was the first production pathway for synthetic aviation fuel to receive ASTM approval (ASTM D7566 Annex 1). Approval for this fuel, referred to as FT-SPK (Fischer–Tropsch synthetic paraffinic kerosene), was granted in 2009. The South African energy company Sasol was the first to produce synthetic jet fuel using the Fischer–Tropsch method. Originally, coal was gasified to synthetic gas, often called "syngas", which is a mixture of hydrogen (H_2) and carbon monoxide (CO). The syngas was then processed in a Fischer–Tropsch reactor for fuel synthesis. However, ASTM D7566 Makes no reference to coal as a feedstock; it only requires Fischer–Tropsch synthesis with cobalt or iron as catalysts. This means that any feedstock can be used to produce the required syngas. Accordingly, no new certification is required when FT-SPK is produced using syngas from sustainable sources (i. e. green hydrogen and CO_2 from direct air capture).

Many additional production routes have been approved since 2009, covering a huge bandwidth of possible feedstocks (both fossil and renewable).

With a view to e-SAF, three different ASTM routes are available today: FT-SPK (ASTM D7566 Annex 1); FT-SPK/A (ASTM D7566 Annex 4); and the co-processing of intermediate FT products (so-called syncrude) under ASTM D1655 Annex 2. Another process that is promising (at least from a technical perspective) is the so-called methanol-to-jet process, which has yet to be approved; the certification process was initiated at the beginning of 2023.[20]

18 The term co-refining is generally used if renewable feedstocks or intermediate products are processed together with crude-oil-based products within a traditional refinery.

19 CAAFI (2024).

20 Biofuels Central (2023a).

Fully synthetic SAF

Due to the existing standards for synthetic aviation fuel and the respective maximum blending ratios described above, fully synthetic SAF (that is, 100% SAF without any fossil jet fuel) is not used in commercial aviation today. This is primarily attributable to operational safety constaints (e. g. to prevent fuel leaks in older airplanes, a minimum aromatics level is required for proper sealing ring swelling, but aromatics are missing from most SAF options).[21] To become 100% renewable, there are two options, both of which are currently under development by ASTM:

Modifying the fuel: The design of fully synthetic jet fuels could be modified to ensure they meet all relevant specifications fulfilled by Jet A-1.

Modifying the fuel infrastructure (on the ground and in the airplane):[22] Theoretically, fuel infrastructure and airplanes could be 100% SAF compatible. Fully synthetic jet fuels do not pose a problem from a technical perspective, despite their slightly different properties (e. g. lower or no aromatics content). The term "near drop-in fuels" is used to refer to fuels which necessitate adjustments to engine and other parts. Both Boeing and Airbus have already conducted extensive testing with different SAF types.[23] The German aerospace agency DLR has tested a variety of fuels in different assessment campaigns, and DLR concludes that newer airplanes have no problem with 100% SAF.[24] Furthermore, Rolls-Royce has announced that all jet engines currently under production are 100% SAF compatible.[25]

The approval of fully synthetic SAF could have a significant impact on the market ramp-up of e-SAF. Abolishing the requirement to blend SAF with fossil Jet A-1 would mean that every country could potentially produce aviation fuel, without the need for separate SAF and fossil jet fuel storage capacities or blending facilities. While most existing

21 Quante et al. (2023).

22 ASTM (2023).

23 Airbus (2023b), Boeing (2023).

24 DLR (2021).

25 Rolls Royce (2023).

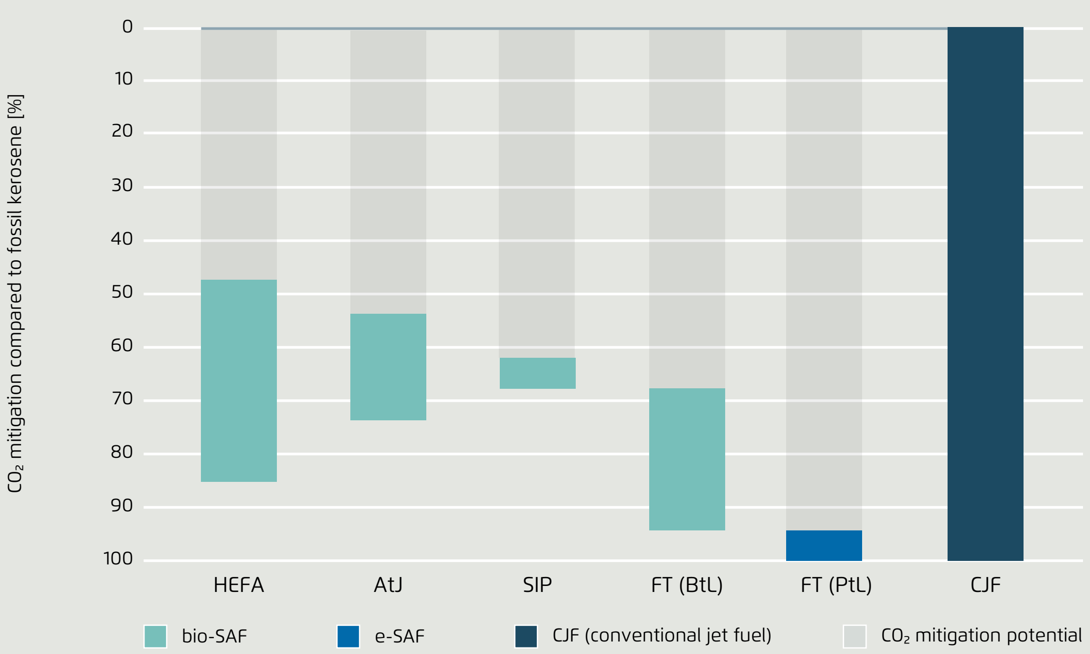
aircraft are currently unable to tank fully synthetic SAF, this problem will diminish and eventually disappear as fleets are gradually replaced. New infrastructure could be designed for compatability with the new standards and fuel types, and only one fuel qualification process would be necessary, as opposed to the current need to approve production of the Jet A-1, the SAF, and the blend. For these reasons, 100% SAF fueling could become a factor that promotes economic growth, particularly in developing and emerging countries.

2.3 The GHG reduction potential of SAF

A widely used method for comparing the GHG emissions of various fuels is life-cycle analysis, or LCA. The LCA method enables estimation of the emissions incurred from initial production up to final use (that is, from "well-to-wake"). Accordingly, it can be used to compare the climate mitigation potential of different SAF production routes (including feedstocks; see Figure 7). However, one must keep in mind that direct CO_2 emissions are only responsible for about one-third of the climate impact of aviation. Non-CO_2 effects, including nitrogen oxides (NO_X), vapour trails, and cloud formation, account for the other two-thirds.

The key advantage of SAF is that the CO_2 emitted during combustion was previously extracted from the atmosphere, allowing for a closed carbon loop (at least in terms of direct CO_2 emissions). As a result, the overall GHG footprint of a specific SAF is mainly affected by the underlying feedstocks, process design, and power mix. The calculation of GHG emissions from biomass can be particularly challenging, because depending on the type of biomass in question, so-called indirect land-use changes have to be taken into account. If non-food biomass is used for SAF production, usually no direct land competition arises. However, in some cases, biomass supply for fuel production may result in the conversion of untouched land such as rainforest or swamps into

CO_2 mitigation potential of different SAF types compared to fossil kerosene — Figure 7



Agora Verkehrswende and International PtX Hub (2024) | Source: Aireg (2020).

agricultural land, thus resulting in high emissions. Such indirect land-use changes must be considered when estimating the GHG emissions of biofuels, as they can have an enormous impact on the emissions scorecard of a biofuel production route.

By contrast, there are no additional GHG emissions when biofuel production relies on waste inputs (such as agricultural byproducts, forestry residues, or municipal solid waste), as these emissions have already been accounted for. When waste is used as a feedstock, the respective fuel is referred to as an "advanced biofuel" (a term that generally designates a fuel with low GHG emissions). However, the lowest GHG emissions profile is exhibited by e-SAF that is produced from renewable electricity and direct air capture (DAC) of CO_2. Given 100%-renewables-based e-SAF, the (smaller) GHG footprint is attributable to wind and PV plant construction, fuel synthesis, and CO_2 supply.

3 | What is e-SAF and how is it produced

"E-fuel" (including e-SAF) is a collective term for fuels typically produced from green hydrogen and CO_2 or, in the case of e-ammonia, from green hydrogen and nitrogen. Here, the "e" stands for the electricity used to produce the hydrogen. At the European level, such fuels – together with green hydrogen – are also referred to as RFNBOs, i. e. "renewable liquid and gaseous transport fuels of non-biological origin". The process technologies used to produce e-fuels are generally referred to as power-to-X (PtX) processes.

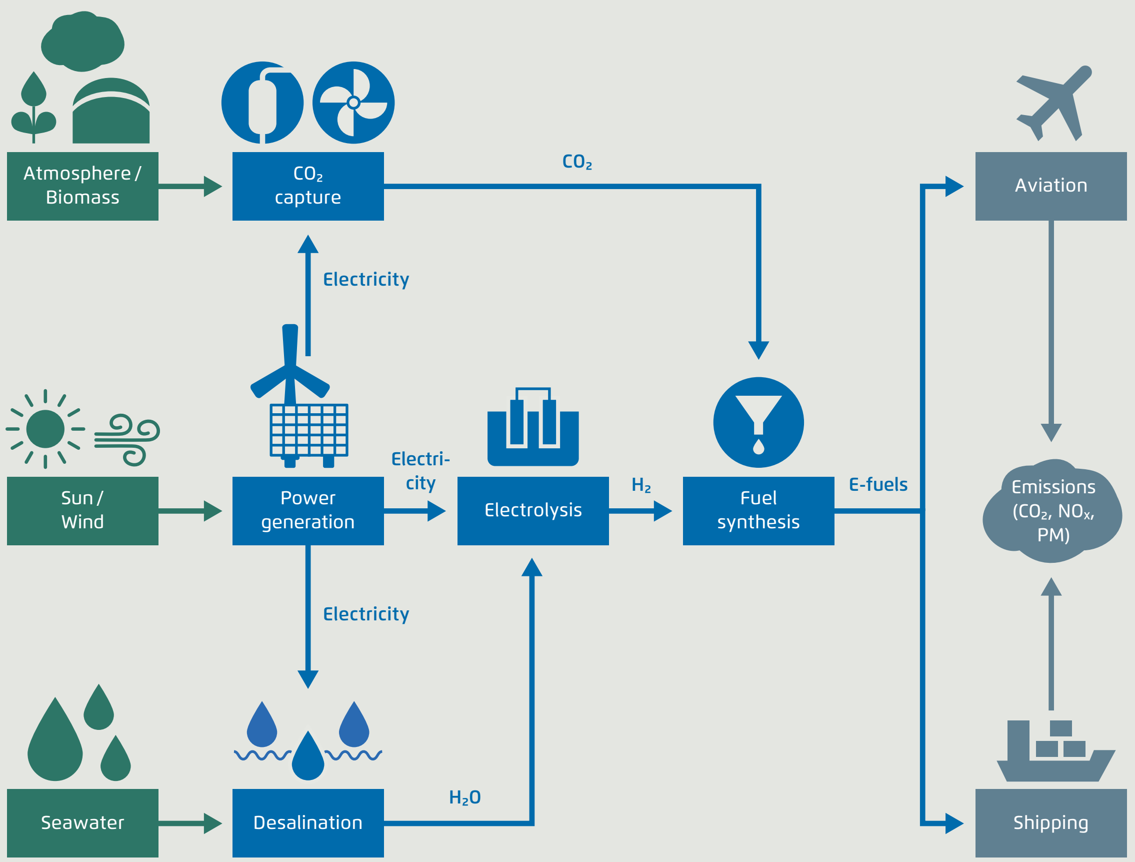
The "X" stands for the respective target product: If gaseous fuels such as synthetic methane are to be produced, one speaks of power-to-gas (PtG) processes; if the target product is liquid fuels such as gasoline, diesel, or jet fuel, then one speaks of power-to-liquid (PtL) processes. In some cases, e-fuels are thus also referred to as PtX, PtG, or PtL fuels.

Since e-fuels are produced using chemical synthesis processes, they may also be referred to as synthetic fuels. However, e-fuels are often misleadingly confused with synthetic fuels. Although they are produced using the same synthesis processes, the synthesis gas may be generated from other sources (e. g. coal or biomass gasification, or natural gas or biogas reforming). E-fuels are thus always synthetic fuels, but synthetic fuels are not always e-fuels.

If the hydrogen required for this synthesis is produced based on electrolysis from renewable electricity (to

Targeted e-fuel production for aviation and shipping

Figure 8

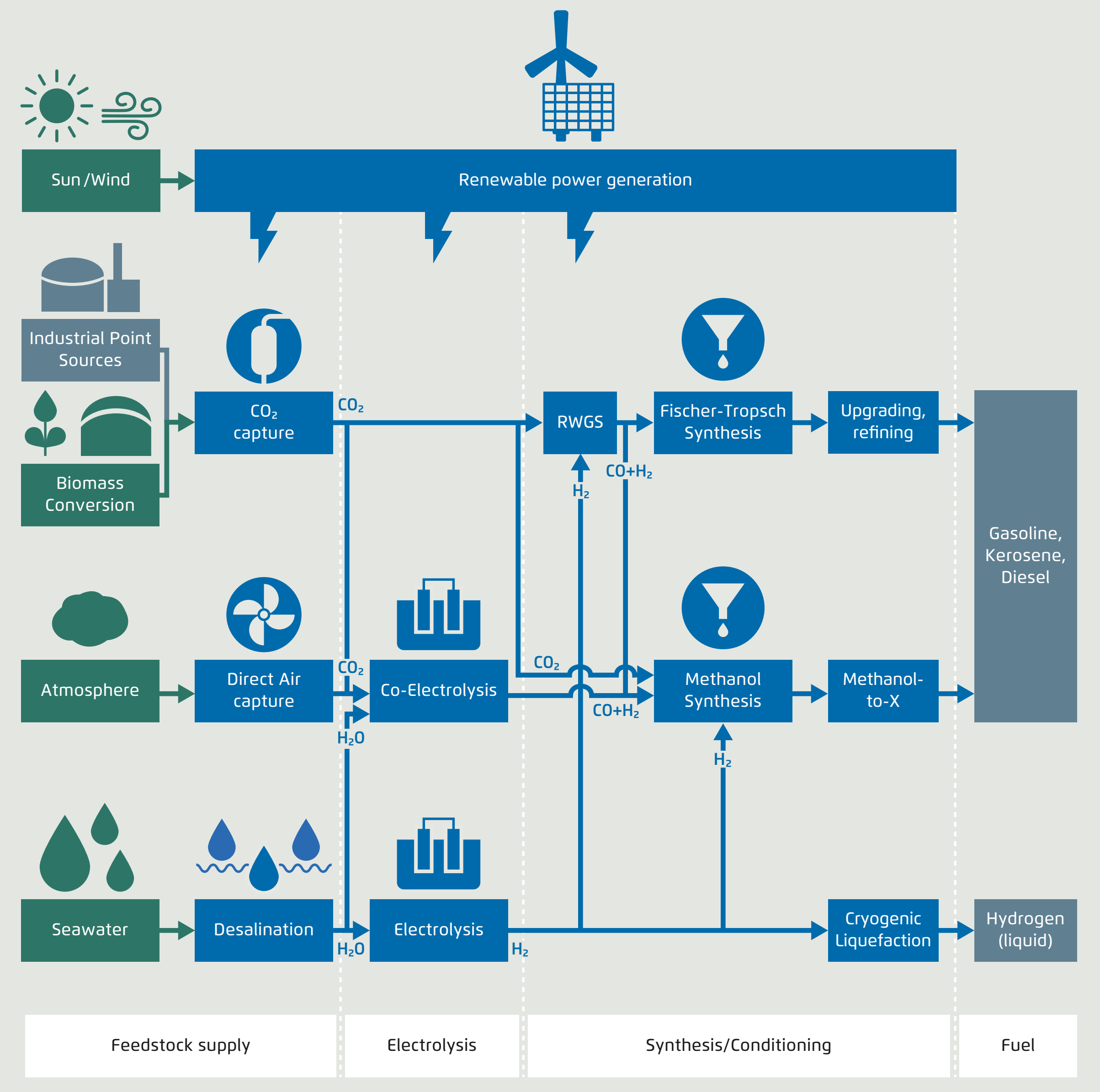


Agora Verkehrswende and International PtX Hub (2024) obtain green hydrogen) and the required CO_2 is extracted from the atmosphere,[26] these fuels are virtually CO_2-neutral. This is not the case when the CO_2 is captured from industrial processes (e. g. glass or cement production) based on a fossil feedstock or energy carrier. Known as capture from an "industrial point source", this can be seen as cascade use of the fossil CO_2 from the original processes. The e-fuels produced in this manner could replace fossil transport fuels, but would emit addi-

26 This is provided either technically with the help of direct air capture (DAC) systems or the CO_2 is first bound in biomass via photosynthesis, which is then converted to make the CO_2 usable again.

Overview of e-fuel production processes

Figure 9



Agora Verkehrswende and International PtX Hub (2024) | Note: RWGS = Reverse water gas shift.

tional CO_2 into the atmosphere. Thus, in the long term, they do not represent sustainable sources of CO_2 in a climate-neutral world.[27]

Due to residual emissions that are difficult to avoid (e.g. from the construction of the required wind turbines and PV systems), e-fuels are not – as is often assumed – climate neutral, but they have a significantly lower impact on the climate. Since most e-fuels are still carbon-based (due to the CO_2 used for their production), they cannot contribute to transport-sector decarbonization (that is, the avoidance of CO_2 emissions), but rather only to transport-sector defossilisation (that is, the avoidance of fossil feedstock/fuels). An exception to this is ammonia, which is discussed as a fuel for maritime shipping and is not based on carbon, but rather on nitrogen. However, as nitrogen-based aviation fuels remain largely theoretical at present, we do not address them any further here.

3.1 Defining e-SAF

To date, there is no generally accepted system of classification for e-SAF production processes. While the basic production procedure is similar in each case, the individual process steps, operating conditions, and outputs can vary significantly. Most processes require green hydrogen (i.e. hydrogen produced from water electrolysis using renewable electricity) as a starting input. This hydrogen is then combined with carbon dioxide (CO_2) to synthesize hydrocarbons. These synthetic hydrocarbons can be used directly as a fuel or processed further. Figure 9 provides an aviation-focused overview of process routes, feedstocks, and target products.

While intensive research has been carried out in recent years concerning e-SAF production methods, industrial-scale production has not yet been realized. Many of the associated technologies have been established for decades and represent mature technologies. However, novel engineering challenges are posed by the need to produce green hydrogen based on fluctuating renewables and carbon from a renewable source in combination with downstream synthesis processes.

27 For a differentiated assessment of CO2 sustainability, see section 4.

With a view to PtL-SAF or e-SAF, there are two main production routes: Fischer–Tropsch synthesis (FTS) and Methanol-to-Jet (MtJ). Both processes combine hydrogen (H_2) and carbon (C) to yield a hydrocarbon-based fuel. In the MtJ process, e-methanol is produced as an intermediate product, which can easily be transformed into e-kerosene. The e-methanol itself can directly be used as a marine fuel or base chemical, and therefore has flexible market applications. The output of Fischer–Tropsch synthesis is a syncrude, which is similar to crude oil and can be used to produce kerosene. However, FTS always produces naphtha and diesel as secondary products. Current research is focused on increasing the share of kerosene produced in the process (so-called "kerosene selectivity") by minimizing the diesel fraction. Nevertheless, the secondary products are commercially valuable, and can be sold in various markets.

The next subsections discuss processes for obtaining hydrogen and CO_2 and provide additional details concerning synthesis routes.

3.2 Feedstock supply

Various technical options are available to obtain the feedstocks required for e-fuel production (water, hydrogen, and nitrogen/CO_2).

Water: seawater desalination and treatment

Large quantities of water are required to produce green hydrogen. Specifially, some 10 kilogrammes of water is required per kilogramme of hydrogen produced in a stoichiometric reaction. Most electrolyzers require ultrapure water, such that even input water of drinking-water quality must be further purified to remove salts and minerals. This purification usually takes place in a water treatment plant directly upstream from the electrolyzer. Researchers are also exploring the direct use of brackish water and seawater as a feedstock. However, such technologies are still confined to the laboratory.[28]

In order to supply high volumes of water without adverse effects to groundwater – especially in "sweet spots" for renewable power generation, which are often arid – seawater desalination plants are typically required. Such

28 Asghari et al. (2022).

plants are already being used worldwide to supply drinking water to households and industry, and can thus be considered a mature technology. The most common desalination method is "multi-stage flash evaporation", in which seawater is evaporated by adding heat (often waste heat from nearby power plants) in several condensation stages. Due to the high energy requirements of this process, reverse osmosis plants are also increasingly being used as an alternative. In this process, seawater is forced through a membrane under high pressure, allowing separation of salt and other impurities. Seawater desalination plants require electricity to operate, although the associated power consumption is significantly lower than that of electrolysis. In addition, special attention must be given to the leftover brine (highly concentrated salty runoff). This by-product has to be carefully reintroduced to the sea or completely evaporated to avoid harming local marine life.[29]

Hydrogen: electrolysis

In the context of green hydrogen production, electrolysis is generally understood as the splitting of water (H_2O) into hydrogen (H_2) and oxygen (O_2) using renewable electricity. Depending on the temperature level at which this process takes place, a distinction can be made between so-called low- and high-temperature electrolyzers. Currently, the most widely used technology in the first case is alkaline electrolysis (AEL), in which an alkaline solution is used as the electrolyte. Against the backdrop of increasing feed-in from fluctuating renewables, polymer electrolyte membrane electrolysis (PEMEL) has become established as another low-temperature electrolysis technology in recent years, due to its higher compatibility with fluctuating loads. Solid oxide electrolysis (SOEL), often referred to as high-temperature electrolysis, operates at significantly higher temperatures and requires water vapour (instead of liquid water) as an input, but is characterized by higher efficiencies than the low-temperature processes. A variant of SOEL is the co-electrolysis, in which CO_2 and water vapour are used simultaneously as a feedstock, directly producing a synthesis gas consisting of hydrogen and carbon monoxide (CO), which can be used for subsequent (fuel) synthesis. Compared to the low-temperature electrolyzers now established on the market, the high-temperature processes have only been realized in smaller demonstration plants.[30]

29 Jones et al. (2019).

30 IEA (2022).

CO_2: biomass and direct air capture

There are essentially two different ways of artificially capturing CO_2 from the atmosphere: either directly via direct air capture (DAC) or indirectly via biomass. In the latter case, CO_2 is absorbed during photosynthesis and released during subsequent conversion (e. g. in biomass combustion or in biogas/bioethanol production). In biogas and bioethanol production, CO_2 is produced as a by-product of the biological conversion processes in relatively high concentrations, requiring comparatively low additional purification. As a by-product of combustion processes, CO_2 is present in the exhaust gas in a considerably lower concentration and must be separated and purified with considerably higher effort.[31]

The DAC process, by contrast, is used to capture CO_2 directly from the atmosphere. This process follows three basic steps: first, by means of fans, large amounts of ambient air are directed through a device in which the air passes over a sorbent, which binds the CO_2 (and, depending on the sorbent, water molecules as well). In this way, the carbon dioxide can be separated from the other substances present in the air. In a second step, the air flow is interrupted and CO_2 as well as water are separated from the sorbent, usually by means of thermal energy, so that pure CO_2 is available at the end of the process chain.[32]

3.3 Fuel synthesis

The generic term power-to-liquid (PtL) refers to various synthesis processes for the production of synthetic fuels. This includes Fischer–Tropsch synthesis for the production of synthetic hydrocarbons (e-kerosene, e-diesel), methanol synthesis, and processes for the further processing of methanol into synthetic hydrocarbons (i. e. methanol-to-X processes). Green hydrogen and the respective carrier molecules (CO or CO_2) are required as feedstocks in all these processes.

Fischer–Tropsch synthesis

The initial chemical process later know as Fischer–Tropsch synthesis was originally developed in the early 20th century for the production of synthetic diesel from

31 ifeu (2019).

32 Viebahn et al. (2019).

gasified coal. Fischer–Tropsch synthesis first requires a synthesis gas consisting mainly of hydrogen and carbon monoxide (CO). To produce e-fuels, this synthesis gas is obtained from the reduction of CO_2 in combination with green hydrogen. This is done via the above-mentioned co-electrolysis, or in a reverse water gas shift (RWGS) reaction. The technical implementation of the RWGS reaction currently represents the greatest technical challenge in e-fuel production. The product of the subsequent Fischer–Tropsch synthesis is a mixture of different hydrocarbons, often referred to as synthetic crude oil, or syncrude for short.

Syncrude can be further processed in conventional refinery processes (including cracking, isomerization, distillation) to produce chemical feedstocks such as naphtha (crude gasoline) or standard-compliant fuels such as diesel or jet fuel. This further processing can take place either directly at the syncrude plant or at existing fossil feedstock (i. e. crude oil) processing refineries. If the syncrude is further processed together with crude oil (or intermediate crude oil products), this is referred to as co-processing. In principle, existing refinery plants can also be used exclusively for the further processing of syncrude after minor technical modifications. E-SAF produced by Fischer–Tropsch synthesis is approved as a blending component in civil aviation and may currently be blended with fossil jet fuel up to a 50% share.

Today, large-scale Fischer–Tropsch plants exist, but so far they are exclusively used for fossil feedstock conversion, such as coal (coal-to-liquids, CtL) or natural gas (gas-to-liquids, GtL). The world's two largest GtL plants, QatarEnergy's and Shell's Pearl GtL plant and QatarEnergy's and Sasol's ORYX GtL plant, both in Ras Laffas, Qatar, have a combined production capacity of 8.5 million tonnes per year.[33] Work has also been underway for several years to use biomass (biomass-to-liquids, BtL) or waste materials (waste-to-liquids, WtL) as feedstocks for Fischer-Tropsch synthesis. The first such industrial plants are currently being built or have recently gone into operation in the USA and elsewhere.[34] They are significantly smaller than the aforementioned plants for processing fossil energy carriers (producing several 100,000 tonnes of synthetic products per year). The first demonstration plants for the production of e-fuels via Fischer–Tropsch synthesis (which are much smaller, with production capacities of about 350 metric tons per year) are currently being commissioned in Germany.[35] Additional larger PtL plants are currently being planned or already under construction.

Methanol synthesis

Methanol is one of the world's most widely produced and traded organic chemical feedstocks. Existing global production capacities are more than 100 million tonnes, and large-scale methanol production (up to 10,000 tonnes per day) is not uncommon. These conventional methanol production plants typically use natural gas or coal as a feedstock.

Renewable methanol can be produced by providing a non-fossil synthesis gas (similar to Fischer–Tropsch synthesis) without significant changes to the established synthesis process. There are several commercial biomass and municipal waste conversion plants currently planned or under construction. In addition to the use of synthesis gas, however, there are also synthesis processes that can convert hydrogen and CO_2 directly as feedstock, i. e. without prior reduction of CO_2 to CO. Given the reduced complexity of these processes, they are seen to be more economical. In addition to smaller demonstration plants for the production of e-methanol – for example, in Iceland (with a production capacity about 4,000 tonnes per year)[36] – much larger plants are planned.

3.4 Fuel processing

Before the synthetic kerosene can be used within aviation, further upgrading and processing steps are necessary to fulfil the given standards on synthetic aviation fuels (mainly ASTM D7566).

Refining of Fischer-Tropsch products

Synthetic jet fuel produced via Fischer–Tropsch synthesis is approved under the standard specification for aviation turbine fuel containing synthesized hydrocarbons (ASTM D7566). It may be blended up to a 50% share with petroleum-based jet fuel (Jet A-1). A prerequisite for

33 Oxford Business Group (2023).
34 Cision PR Newswire (2022a).
35 Atmosfair (2023); P2X Europe (2022).
36 Carbon Recycling International (2023a).

e-kerosene to be used in commercial aircraft is hydroprocessing, for which mainly three different processes are applicable, i. e. hydrocracking, hydrotreating, and hydroisomerization. These processes are technologically mature and are used today in conventional refineries to upgrade crude oil.[37]

Hydrocracking involves the catalytic conversion of long-chain hydrocarbons into short-chain hydrocarbons by the addition of hydrogen. For synthetic kerosene, a chain length of C_8 to C_{17} is targeted. In the process, solid products of the FTS, especially waxes, are transferred into the liquid phase. As waxes and other long-chain hydrocarbons can have a share of more than 80 percent in the obtained syncrude (especially if low temperature Fischer–Tropsch is used), hydrocracking is the central step for syncrude upgrading.[38]

Hydroisomerization is a catalytic process in which unbranched hydrocarbons are converted into branched hydrocarbons. As a result, the low-temperature behavior of the synthetic kerosene is improved, which may be necessary in order to meet the jet fuel freezing point specification of -47 °C. Hydrotreating involves the saturation of double bonds and the removal of heteroatoms such as oxygen with the aim of obtaining fully hydrogenated hydrocarbons.

Methanol-to-Jet

In addition to direct use as a fuel or chemical feedstock, methanol can be further processed into drop-in fuels such as gasoline or jet fuel via various process variants. Here, too, the processes are often named after the target product. Methanol-to-gasoline (MtG) refers to the production of gasoline and methanol-to-jet (MtJ) to the production of jet fuel. These processes are similar in terms of basic process technology and structure, but are currently at different levels of technical maturity. For example, e-SAF via the MtJ route has not yet been approved for use in aviation; a corresponding certification process was initiated at the beginning of 2023.[39]

Plants for the synthesis of gasoline from methanol have been operating for the past century, and a first demonstration plant (with a production capacity of about 450 tonnes per year) for the production of e-fuels started operation in Chile at the end of 2022.[40] In contrast, the process for producing e-SAF from methanol is still at the research stage and only laboratory-scale plants exist to date. However, different industrial technology provider offer MtJ applications, thus larger plants might be realized in the near future.

The conversion and upgrading of methanol to jet fuel can be achieved by combining various applied processes, namely dehydration, oligomerization, and hydrogenation.[41] The first process step is the conversion of methanol into short-chain hydrocarbons. This step is often referred to as the methanol-to-olefins (MTO) process. In the following process step, these short-chain hydrocarbons are combined into hydrocarbons with a carbon number between 8 and 16 via oligomerization, which is the desired kerosene chain length. Within a subsequent hydrogenation process, remaining double bonds are fully saturated by adding hydrogen (via hydrogenation). Although all the individual process steps are known, the combination and optimization of methanol-based jet fuel production can still pose difficulties and requires further research before large-scale implementation. Accordingly, ASTM certification for jet fuel via the methanol route is still pending, and no commercial jet fuel production from methanol is in operation yet.

37 De Clerk (2011).
38 De Clerk (2011), König et al. (2015).
39 Biofuels Central (2023a).
40 HIF (2022).
41 Bube et al. (2024).

4 | Sustainable e-SAF production

Policy measures that aim to reduce emissions have been established and are being further developed at the national and international levels. To demonstrate compliance with emission reduction mandates, systems that monitor and document the use of e-SAF are essential. In this context, it is not enough to consider the emissions directly attributable to e-SAF production and use. Specifically, there is a clear need to adopt frameworks (whether mandatory or voluntary) that take the various dimensions of sustainability into account, including its environmental, economic, social, and governance (EESG) aspects. In this connection, fuel certification schemes that can be used to verify compliance with sustainability critera need to be developed. Last but not least, systems that allow for the credible recording of such sustainability certifications need to be implemented.

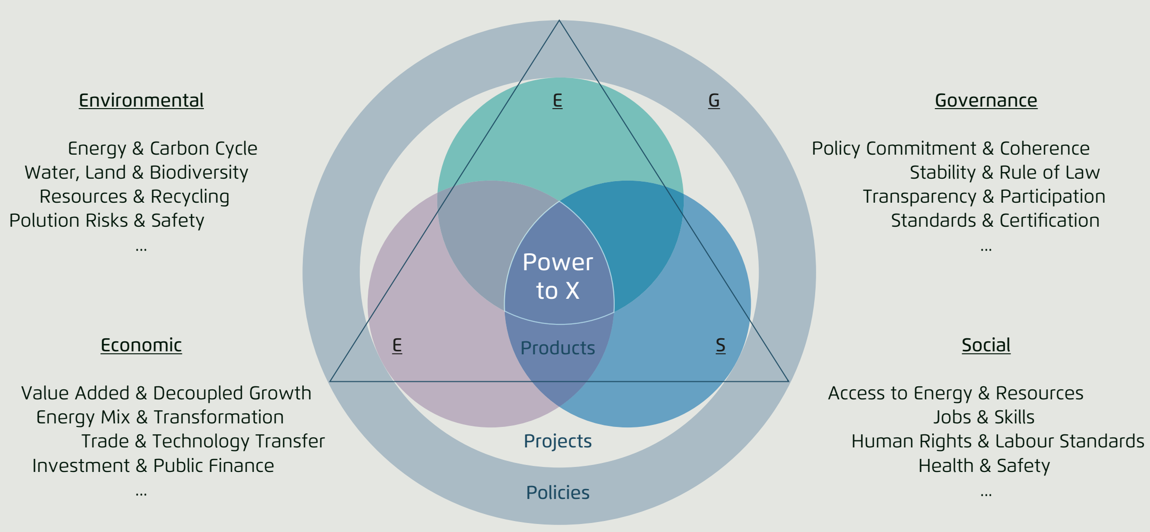
4.1 Sustainability dimensions

Currently, e-fuels are mainly discussed in connection with their potential to reduce CO_2 emissions in transport. However, in addition to furthering climate protection, the development of e-fuel production capacities will have various social and economic impacts. For this reason, we advocate a holistic view of e-fuel sustainability based on the UN's Sustainable Development Goals (SDGs). In this connection, it is necessary to consider the environmental, economic, social, and governance dimensions of e-fuel production and use. At the same time, sustainability measures must always be developed in collaboration with local communities and adapted to their living realities, rather than merely imposed in a top-down manner. Figure 10 provides an overview of these EESG dimensions, as outlined by the International PtX Hub. In the following, we briefly highlight some important aspects of this EESG framework and discuss their implications for the aviation sector and e-SAF production.

The environmental dimension: The sustainable use of feedstocks, land, and materials

New renewables capacity ("additionality"): The production of hydrogen via electrolysis is responsible for a large share of the electricity required to manufacture e-SAF. To keep greenhouse gas emissions from hydrogen production as low as possible, the electricity required in

Combining sustainability dimensions of PtX production: The EESG framework — Figure 10



Agora Verkehrswende and International PtX Hub (2024) the e-SAF production process must come from renewable sources. Yet merely relying on the electricity provided by the existing power supply system is problematic in many localities, due to the high share of generation from fossil fuels. Furthermore, as renewable power is still scarce, it should be used directly and in the most efficient manner possible in order to avoid conversion losses and minimize fossil-based power demand. Accordingly, it is necessary to develop additional renewable electricity generation capacities that are dedicated to hydrogen production (thus fulfilling the criterion of "additionality"). This will prevent hydrogen production from competing with renewables expansion in the existing grid.[42]

Closed CO_2 cycle: In addition to hydrogen, the synthesis of nearly climate-neutral e-SAF requires CO_2 from a closed lifecycle. This means that only carbon from DAC or biogenic sources, preferably residues, should be used. DAC is site-independent and promises to make CO_2 from the atmosphere directly available for e-SAF synthesis. However, the technology has significant space and energy requirements, due to the low concentration of CO_2 in the atmosphere, and it is not yet deployable at scale. Accordingly, only a limited amount of CO_2 is available using DAC at present, and as a method it remains very expensive.

By contrast, biogenic CO_2 (e. g. from biogas or bioethanol plants) is available today, and is relatively inexpensive. However, there are various risks to sustainable deployment at scale, due to land-use competition with the food industry and indirect land-use changes. Overall, the availability of sustainable biogenic CO_2 at scale is sharply limited.[43]

Ecological seawater desalination: One litre of e-SAF requires about 3.6 litres of purified water, mainly for hydrogen electrolysis. Geographically there are few locations that offer both good conditions for renewables production as well as sufficient volumes of sweet water. While many regions may initially seem attractive for the production of e-fuels due to their high solar energy potential, such regions often lack sufficient (surplus) water resources. Large-scale seawater desalination represents a possible solution moving forward. According to recent studies, more than 85% of the currently planned green hydrogen projects might require water sourced through desalination.[44] However, the energy required to run such desalinisation plants must come from renewables, in order to maintain the positive CO_2 balance of e-fuels. In addition, desalination creates brine (i. e. hypersaline water), the disposal of which must be regulated.[45]

Avoiding land-use competition: The production of e-fuels requires less land than the production of biofuels based on energy crops such as soy, corn, or canola. Nevertheless, the land-use requirements for all associated systems (including DAC plants, PV systems, and wind turbines) are significant. These land-use requirements can be minimized through various approaches, such as wind-turbine placement amid pastures, or the dual use of land for solar energy production and agriculture ("agrophotovoltaics"). Regarding the possible implications e-SAF production for biodiversity, environmental permitting procedures need to ensure fuel and renewables production is not sited in close proximity to important natural landscapes or protected areas.[46]

Circular raw material use: Depending on the applied technologies, various metals, including platinum and iridium, are required for e-SAF production technologies (e. g. as catalysts in the synthesis process, and to manufacture electrodes for electrolysis). Platinum and iridium are rare metals and currently only mined in a few global locations. For this reason, further research is required not only with a view to reducing the volume of metals required from a technical perspective, but also concerning the potentials for substitution and recycling, which is currently only carried out to a limited extent.[47]

The economic dimension: Local value creation and use cases for e-SAF

Long-term economic development: To ensure that the benefits of future e-fuel projects are not limited to additional tax revenues or profit streams for the state,

42 Agora Energiewende; Agora Industrie (2022).
43 Viebahn et al. (2019); ifeu (2019).
44 IRENA (2022).
45 BHL; LBST (2022); WIRED (2019); IRENA (2022)
46 Jeswani et al. (2020); Fraunhofer ISE (2022); PtX Hub (2022).
47 Fraunhofer ISE, E4tech, Fraunhofer IPA (2018); Bahadur et al. (2018).

strong linkages to local economic structures should be encouraged. Insofar as local economic actors can be successfully integrated into the e-SAF value creation chain (both upstream and downstream), this promises to create positive impulses for the formation of new companies as well as for investment and innovation. This, in turn, can support sustainable economic development and the creation of high-quality jobs over the long term.[48]

48 Altenburg et al. (2023).

Forward and Backward Linkages

The production of e-SAF (and of intermediate products such as green hydrogen and methanol) presents various opportunities for creating forward and backward linkages to the domestic economy and thus for contributing to sustainable socioeconomic development. Moving up the supply chain, local suppliers can provide finished systems, components, and other inputs to the e-SAF plants (e.g. solar panels, wind turbines, electrolyzers, and other necessary services and technologies). Insofar as local production capacities are lacking, targeted investment and capacity building measures could be promoted (see below).

Furthermore, synergies can be created between e-SAF production and the agricultural sector (in which CO_2 from biomass is produced). In some arid locations, the shade provided by the solar panels combined with smart irrigation and fertilization measures could potentially create new fertile land. Moving down the supply chain, the produced e-SAF has a higher commercial value than the hydrogen itself and can generate significant export revenues. However, e-SAF also offers significant opportunities for the defossilisation of domestic aviation, which could create local demand (see below). Also, where applicable, the intermediate products hydrogen and green methanol could contribute to the greening of local industries such as shipping, mining, chemicals, or steel. In places where these industries do not yet exist, beneficial production conditions for green energy carriers could further lead to the attraction of energy intensive industry (such as steel), with beneficial effects for job creation and local value added ("renewables pull effect"). Lastly, other industries stand to benefit indirectly from foreign direct investment in e-SAF production and associated renewable capacities. Prior agreements between domestic policy makers and investing companies could stipulate that additional renewable capacity must be built; this would benefit local companies and the population at large. In this way, e-SAF production can encourage a just transition with wide-ranging benefits for economic development, innovation, job creation, and human capital formation.

The domestic energy transition: Electricity supply remains inadequate in many countries that have good preconditions for e-fuel production. Furthermore, in many places, fossil-fuel power plants operate with poor efficiency. On the one hand, there is a risk that focusing on e-fuel production will run at cross purposes with the efficient development of domestic renewables or the decarbonization of the power supply mix, particularly in "sweet spot" locations with favourable conditions for renewables. On the other hand, improving power infrastructure comes with high costs that may be difficult to afford, especially in low-income countries. The investments made in connection with e-fuel projects to provide additional power generation could offer an opportunity to advance the development of infrastructure that serves local needs, and not just that of the e-fuel project. Accordingly, e-fuel projects should strive to overbuild infrastructure capacities, including that of the power grid, in the countries in which they take place.[49]

Strengthening use cases in aviation: Usage close to production decreases the cost of transporting e-SAF and thus generates cost advantages, which may attract airlines to purchase these fuels. This could strengthen air traffic hubs in SAF producing countries, and create jobs in associated supply chains (e.g. for the operation and maintenance of local transport and fueling infrastructure). In addition, environmental benefits can be obtained by increasing local offtake of e-SAF as well as by shortening fuel transport routes.

49 Afful-Dadzie et al. (2020); United Nations (2023).

The social dimension: Supporting a just transition

Occupational training: The ramp-up of e-SAF production can have significant impacts on the labour market. By way of example, if jobs in fossil fuel extraction are lost or if parts of the economy migrate to regions with better conditions for renewables, this can create socioeconomic dislocation. Occupational training programmes, including programs to retrain workers, are thus essential to minimize negative impacts to the workforce. Cooperation between countries in the domain of technology transfer can strengthen local economic capacities. A related but no less important issue is to ensure domestic officials have the expertise required to formulate and enact effective regulatory and industrial policy.

Access to electricity and drinking water for the population: E-SAF production creates significant demand for electricity and drinking water that can potentially threaten security of supply for local populations, especially in precarious regions. Therefore, e-SAF production could trigger or intensify resource conflicts. The construction of additional renewable generation and desalination capacities can mitigate this risk and help to ensure water and electricity access for local populations.[50] One possible model is to undertake such additional investment using public–private partnerships that are structured to produce benefits for both local communities and investors.

Land use rights: Large-scale projects in the energy sector require considerable amounts of land and historically such projects have sometimes resulted in violations of land-use rights. To ensure that such rights are upheld, governance procedures should be established by the project principles (both public and private) that enable the genuine participation of local peoples. This should include the creation of platforms for soliciting opinions from civil society. In addition, transparent complaint mechanisms (e. g. based on the principle of Free, Prior, and Informed Consent, or FPIC) should be established.[51]

Human rights and labour standards: It is important to ensure that the operators of e-SAF plants adhere to relevant human rights and labour standards, including those set forth in the UN Guiding Principles on Business and Human Rights (UNGP), the ILO Core Labour Standards, and the OECD Guidelines for International Enterprises, including the OECD's Due Diligence Guidance. These requirements and standards include the prohibition of forced child labour and of discrimination against women. Monitoring mechanisms are also needed to ensure health and safety compliance.[52]

50 Pacific Institute (2023).

51 Backhouse (2019); International PtX Hub (2024a).

The governance dimension: Steering structures for sustainable e-SAF development

As discussed in the foregoing, the development of e-SAF production can have negative consequences for people, the economy, and the environment – yet it can also present numerous opportunities.

Governance aspects are crucial for ensuring sustainability within the first three dimensions. More specifically, policymakers have a responsibility to develop comprehensive regulatory frameworks that guarantee fulfillment of the other dimensions of sustainability. This necessitates first and foremost comprehensive international standards and certifications that offer clarity and guidance for stakeholders, including airline industry actors. SAF standards and certification systems are the focus of the next section. To be sure, implementation will be a complex endeavour, and will depend on the policy commitment of each individual country. Yet to avoid market fragmentation, the transformation of the aviation industry must be addressed based on a comprehensve, global approach. Close and trusting international cooperation will be essential for making progress on these issues.

Furthermore, the decision to engage in bilateral or multilateral e-SAF partnerships between countries will depend on political stability and a commitment to rule of law. E-SAF projects will crucially depend on the transparency and stakeholder buy-in that is facilitated by standards, certifications, and other governance frameworks. Particularly when investment in a given country is exposed to high corruption risks, the managers of international e-SAF projects will need to perform adequate due diligence and insist on robust monitoring procedures to ensure project compliance with relevant standards.

52 OECD (2018).

4.2 Sustainability standards and criteria for aviation

Based on the sustainability dimensions described in the prior section, what tangible steps are required to assure e-SAF is sustainably produced? A first prerequisite is the adoption of internationally recognized standards. Subsequent to this, certification mechanisms must be put in place, to ensure standards are being fulfilled.

In this connection, it is important to distinguish between "certification" and "standard", as these two terms are often used interchangeably. A "certification" is a "stamp of approval" conferred by an independent auditor that verifies the compliance of a product or process or product. The term "standard", by contrast, refers to the specific requirements and specifications that are to be fulfilled, whether in relation to technical aspects (e. g. to ensure safety) or sustainability (e. g. to ensure environmental protection).

Example 1: Technical standards

The ASTM (American Society for Testing and Materials) plays a key role in defining technical standards for aviation fuels. In this connection, the global standard for SAF in aviation is ASTM D7566.

Example 2: Sustainability standards

In the aviation sector, the most relevant international sustainability standard implemented thus far is CORSIA (Carbon Offsetting and Reduction Scheme for Aviation). CORSIA has been adopted by the International Civil Aviation Organization (ICAO) as a global offsetting scheme to ensure carbon emission reductions in international aviation.[53] Compliance with CORSIA can be achieved though various means, including use of SAF. The respective sustainability criteria are laid out in the "CORSIA Sustainability Criteria for CORSIA Eligible Fuels".[54] Table 2 summarizes the primary sustainability requirements that must be fulfilled by CORSIA-eligible SAF.

53 For further information on CORSIA and its effects on airlines, please refer to South Pole (2023).

54 These criteria are officially included in the CORSIA scheme through Annex 16, Volume IV to the Convention on International Civil Aviation; see ICAO (2022a).

Main sustainability requirements for CORSIA-eligible SAF — Table 2

Theme	Principle
Greenhouse gases (GHG)	Should generate lower carbon emissions on a life cycle basis.
Carbon stock	Should not be made from biomass obtained from land/aquatic systems with high biogenic carbon stock.
GHG reduction permanence	Should lead to permanent reductions in emissions.
Water	Should maintain or enhance water quality and availability.
Soil	Should maintain or enhance soil health.
Air	Should minimize negative effects on air quality.
Conservation	Should maintain biodiversity, conservation value, and ecosystem services.
Waste and chemicals	Should promote responsible management ofwaste and use of chemicals.
Human and labour rights	Should respect human and labour rights.
Land-use rights and land use	Should respect land rights and land use rights, including indigenous and/or customary rights.
Water use rights	Should respect prior formal or customary water use rights.
Local and social development	Should contribute to social and economic development in regions of poverty
Food security	Should promote food security in food insecure regions.

Agora Verkehrswende (2024) | Source: ICAO (2022a).

In addition to CORSIA, there are other national and international standards. For example, the EU has established a regulatory standard that provides for hydrogen and hydrogen-derived fuels such as e-SAF to be recognized as "renewable fuels of non-biological origin" (RFNBOs).[55] However, a certification system that verifies compliance with this standard has yet to be adopted.[56]

The EU has also introduced mandatory blending quotas for SAF with its ReFuelEU Aviation legislation, which entered into force in October 2023. EU member states are under an obligation to ensure that fuel suppliers comply with these quotas. This legislation achieves two aims: First, member states must now report on targets set by the EU; and second, fuel suppliers now have an obligation to introduce RFNBOs to the EU market.

4.3 Sustainability certification

Certification is a tool used to verify compliance with recognized standards. The granting of certification depends on a clear and objective assessment process (e. g. for evaluating the sustainability of a given product, such as e-SAF).[57] Certification provides assurance to market participants that the hydrogen, e-kerosene, or the e-SAF they are buying, selling, or using adheres to specific criteria. Usually, the certification process includes an audit carried out by independent body to verify compliance.

Certification is also relevant for the conception and implementation of e-SAF investment projects. Depending on the off-take market in question (e. g. EU, US, global), certain certifications may be required to sell the product. Accordingly, in the run-up to an investment decision, stakeholders may require confirmation that a project developer possess or can obtain relevant certifications.

Certification processes

The criteria that are assessed under a certification process may vary. The CORSIA criteria listed above furnish just one example. A certification system may also have various levels of certification (with some products fulfilling the criteria for "plus" or "gold" level certification).

The broader certification ecosystem

The broader certification ecosystem is comprised of various actors and systems, including ICAO and EU regulatory bodies, industry-led certification schemes, independent third-party auditors, and "system users" (i. e. companies). (Figure 11). While the ecosystem portrayed below is native to the EU, all such ecosystems will generally have a overarching regulatory stakeholder and third-party auditors.

The individual certification systems or schemes verify compliance withthe criteria established by a particular standard. For example, under the CORSIA Eligibility Framework and Requirements for Sustainability Certification Schemes, two certification schemes have been approved – namely, ISCC (International Sustainability and Carbon Certification) and RSB (Roundtable on Sustainable Biomaterials). Each of these systems has specific guidance on how to certify CORSIA eligible fuels (and establish "ISCC CORSIA" or "RSB CORSIA" certification). Similar schemes have been approved under the EU RED Renewable Energy Directive (RED) for certifying bio-SAF. These fuels can be claimed under the EU Emission Trading System (ETS) or EU RED. However, to date, neither CORSIA nor the EU have officially recognized any e-SAF certification schemes. In the case of CORSIA, the sustainability criteria for e-SAF still have to be defined. In the EU, by contrast, criteria for e-SAF were only recently adopted; the approval of associated certification schemes remains pending.[58]

Aside from official certification under binding regulatory frameworks, there is also the voluntary market. Voluntary schemes are particulary relevant in the area of aviation fuels, as numerous partnerships have arisen that aim to reduce carbon footprints with SAF. In this connection, certification is important, for it allows companies to demonstrate reduced GHG emissions or other sustainability benefits. Often, the associated cooperative initiatives are voluntary, meaning they are not based on government regulations or policy, but rather a corporation's

55 This standard was established with the 2022 recast of the RED II in combination with Delegated Acts to Articles 27 and 28, which entered into force in July of 2023; see European Commission (2023a).

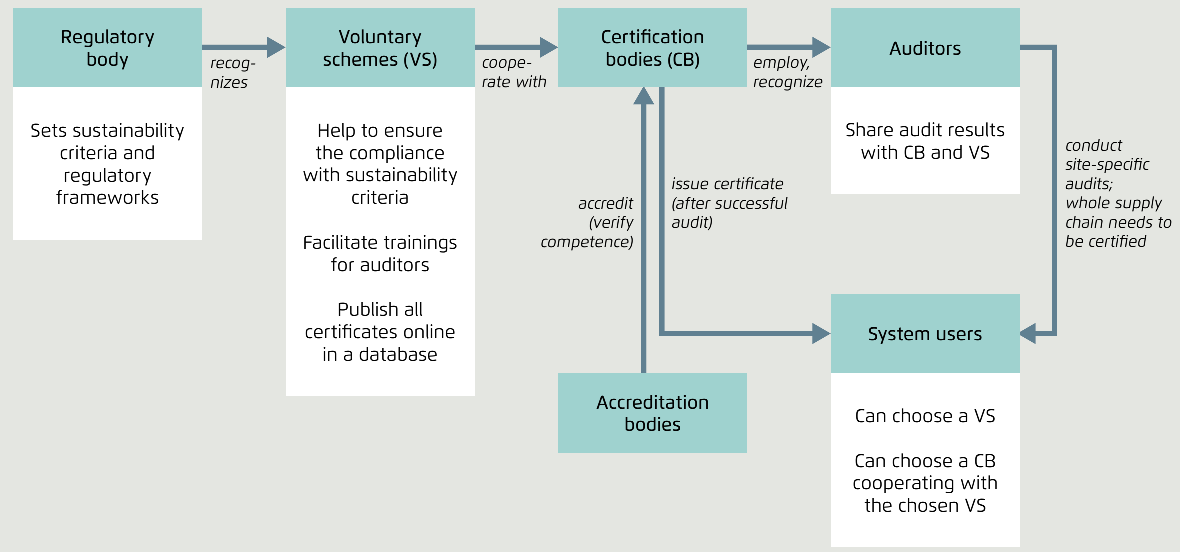
56 Additional information concerning this regulatory framework can be found in International PtX Hub (2023a).

57 See International PtX Hub (2023b).

58 European Commission (2024).

Example of a certification ecosystem: The regulatory ecosystem established by RED II

Figure 11



Agora Verkehrswende and International PtX Hub (2024)

own commitment to sustainability. Some of the certification schemes mentioned above additionally offer certification solutions for the voluntary market.

4.4 Accounting: the book and claim approach

In the future, airlines will need to demonstrate compliance with SAF quotas and/or claim their SAF usage under emissions trading schemes (ETS). To perform the associated accounting for proof of sustainability (PoS), there are various so-called "chain of custody" models; the most common are: (i) physical separation, (ii) mass balance; and (iii) book and claim. Each of these approaches has specific advantages and disadvantages. Under the physical separation and mass balance models, certification and reporting are linked to the physical fuel and its migration through the value chain. By contrast, the book and claim model is a purely virtual trading system. In terms of SAF accounting, the book and claim approach is seen as most promising for assuring SAF can be fueled and credited in a highly distributed manner. Under this model, SAF quantities that are produced and consumed are reported to a central entity, thus ensuring transparent and centralized verification (see Figure 12). The adoption of this model could potentially provide a significant boost to the future development and use of SAF.[59]

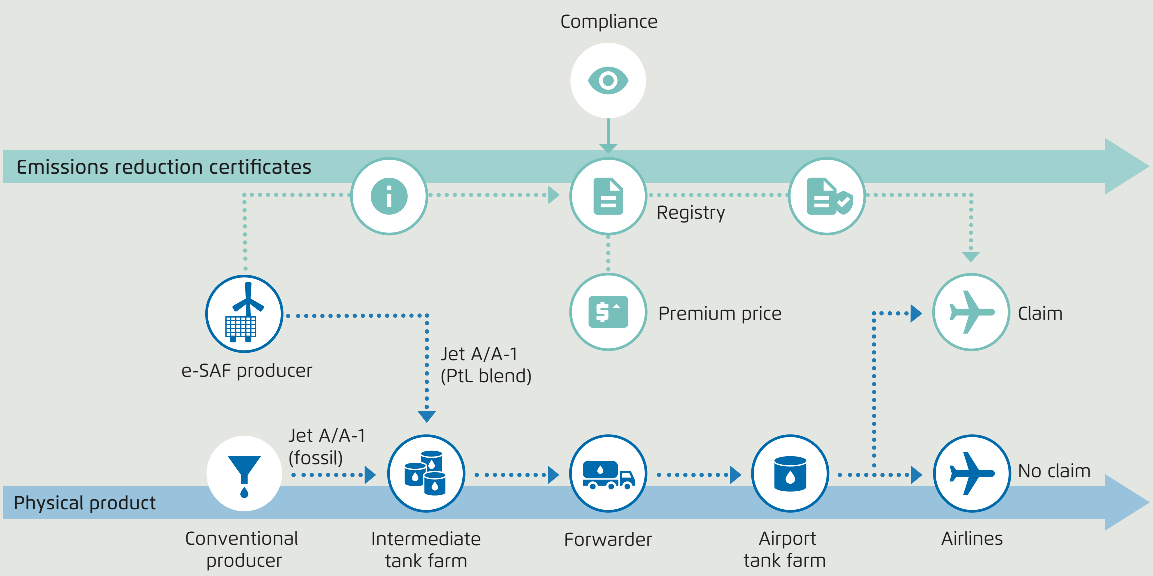
However, such a book and claim approach requires a precise definition of system boundaries, including the licensing of actors authorized to engage in certificate trading and the accurate representation of a certificate's meaning. In this connection, mechanisms must be established to ensure the effective allocation of responsibilities to involved parties. This includes the need to establish a central SAF registry as well as a closed system for the physical transport of SAF fuel to avoid double counting issues and ensure a reliable and transparent market. In general, mechanisms that prevent fraud and ensure integrity are essential aspects of such a system.

The book and claim system relies on transferable certificates that verify the sustainability features of a given quantity of SAF. The issuing body grants these certificates to fuel manufacturers; the certificates indicate the

59 Pechstein et al. (2020).

Visualization of the book & claim process

Figure 12



Agora Verkehrswende and International PtX Hub (2024)

amount of SAF added to the fuel supply system, after blending with conventional jet fuel. SAF manufacturers are responsible for producing a specific quantity of SAF and reporting this information to the central registry. At the same time, the system must be designed to ensure that SAF is introduced into a closed system and not accounted for twice. One option is this regard is to operate a closed fuelling system that is controlled by national custom authorities (as already exists to manage tax exemptions for jet fuel). Emission mitigation can then be estimated based on the reported SAF quantities.

A globally recognized book-and-claim system represents a promising solution for the fulfilment of future SAF quotas and for the implementation of SAF in emission reduction schemes. One distinct advantage to the book-and-claim model is that it separates the certificates from the physical product, thus enabling highly distributed fuelling activities. This would enable a global market for emissions reductions, and would sharply accelerate SAF production and use. However, the effectiveness of the system would hinge crucially on well-defined system boundaries, effective monitoring, the licensing of authorized participants, and the creation of a centralized registery. All of these components would need to be robustly designed, to ensure transparency and prevent fraud. Furthermore, the system would need to be made compatible with existing national and supranational SAF legislation.

As a final point, it should be emphasized that a book and claim model would be particularly suitable given e-SAF production in regions with abundant renewable energy resources, such as Brazil, South Africa, Kenya, and Chile, due to the separation of certificates from the physical product. This would eliminate the need to ship SAF over long distances to airports around the world; rather, the fuel could be used in close proximity to production sites. Any airline could claim the climate benefit of SAF by bearing the price difference between standard jet fuel and e-SAF and by making an associated payment to the producer or user of the physical fuel. In this way, the e-SAF could be supplied to any aircraft near the production site, while the airline paying for the cost difference would receive the climate credit.

5 | E-SAF production costs

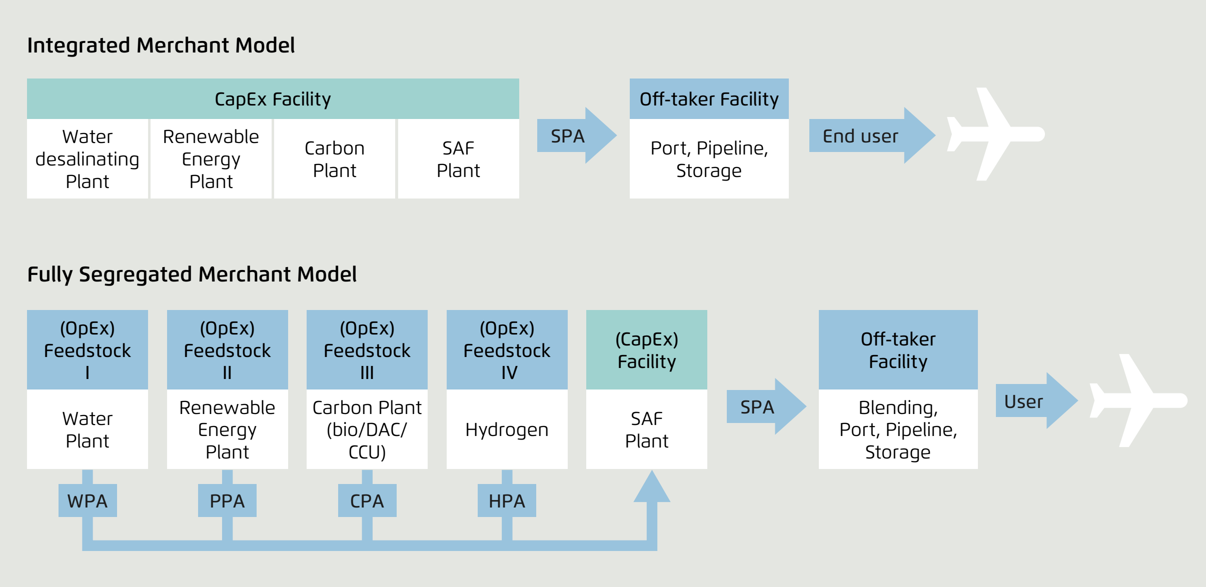
How costly will e-fuels be in future, both for individual users and for the economy as a whole? While the answer to this question is subject to numerous uncertainties, it is possible to develop some preliminary estimates. E-fuel production costs are generally driven by three categories of costs:

- **Operational expenditures (OpEx):**
  Describes all cost associated with the operation of the production facility.
- **Capital expenditures (CapEx):**
  Describes the capital required to construct the production plant.
- **Financial expenditures (FinEx):**
  Describes cost of capital, including costs that accrue to service debt and pay dividends.

The relative weight of each of these cost categories will vary from project to project. Whether expenditures primarily take the form of OpEx or CapEx will depend on the specific merchant model used. In this regard, we can differentiate between an "integrated" and "segregated" merchant model (Figure 13). In an integrated merchant model, the costs associated with the production of all feedstocks (electricity, CO_2, water, etc.) are integrated in the project and thus fall under CapEx. In a fully segregated merchant model, by contrast, the operator does not generate its own feedstocks and therefore enters into purchase agreements for feedstock supply. In this case, the costs for purchasing the feedstocks fall under OpEx. However, mixed variants of these two models are also possible. The following example illustrates the key differences between the integrated and segregated merchant models.

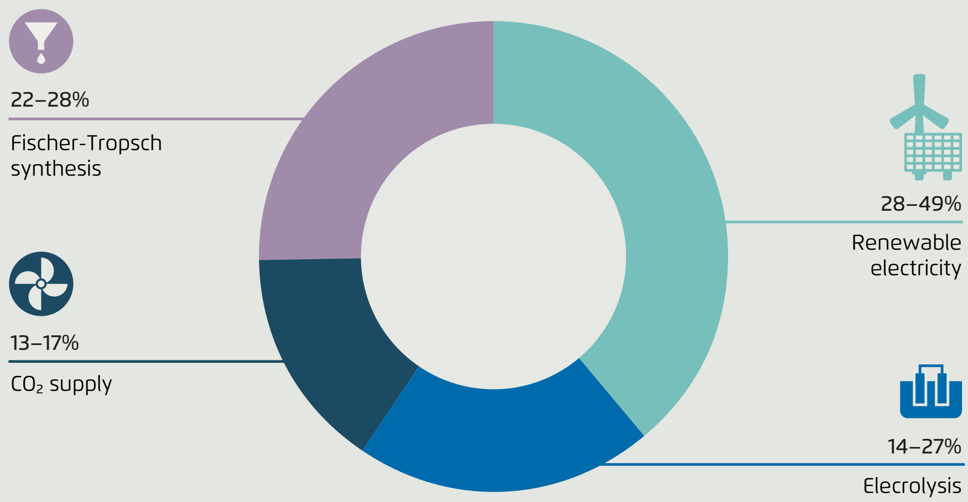
The chart on the next pages shows CapEx components for an integrated merchant model. According to relevant studies, under this model electrolysis and renewable power generation account for more than 50% of e-fuel production costs. Electricity costs account for 28–49% of overall e-fuel production costs. The lower end of this electricity cost range reflects production in geographical sweet spots with favourable weather conditions. Many of these locations are in the southern hemisphere. However, in these regions sustainable CO_2 point sources for large-scale e-fuel production are scarce, making large-scale DAC inevitable. What is more, according to a recent study, CO_2 supply via DAC is likely to cost significantly more than estimated in

Differences in e-fuel cost allocation between integrated and fully segregated merchant models Figure 13



Agora Verkehrswende and International PtX Hub (2024) | Note: CapEx = Capital expenditures, CPA = Carbon purchase agreement, HPA = Hydrogen purchase agreement, OpEx = Operational expenditures, PPA = Power purchase agreement, SAF = Sustainable aviation fuel, WPA = Water purchase agreement.

Capital expenditures and operating costs as an averaged share of e-fuel production costs — Figure 14



Agora Verkehrswende and International PtX Hub (2024) | Note: The cost ranges result from different assumed production locations. Source: dena (2022).

previous, more optimistic studies.[60] Financial expenditures (FinEx) also have a significant impact on production costs. High cost of capital in developing countries can more than offset the production advantages associated with favourable wind and solar conditions. Country-specific credit risk is one main component of cost of capital; the sovereign credit rating is thus strong indication of the cost of capital spread to similar projects in developed countries (Table 3). Credit ratings agencies will take a range of factors into account when assigning a country sovereign credit rating.[61] Obtaining a good sovereign credit rating is usually essential for developing countries to access funding in international bond markets. The following table shows the

60 Sievert et al. (2024).

61 Two of the three biggest rating agencies (S&P and Fitch) assign rankings from AAA to D (for "default"). Moody's, the third major rating agency, has a similar scale that ranges from Aaa to C.

Rating of selected countries and the traded credit spread to German bunds in August 2023 — Table 3

Country	Rating (S&P, 08/23)	Basis point spread to German bunds (08/23)
Kenya	B-	1,398
Nigeria	B-	1,180
South Africa	BB-	772
Brazil	BB-	870
India	BBB-	457

Agora Verkehrswende (2024)

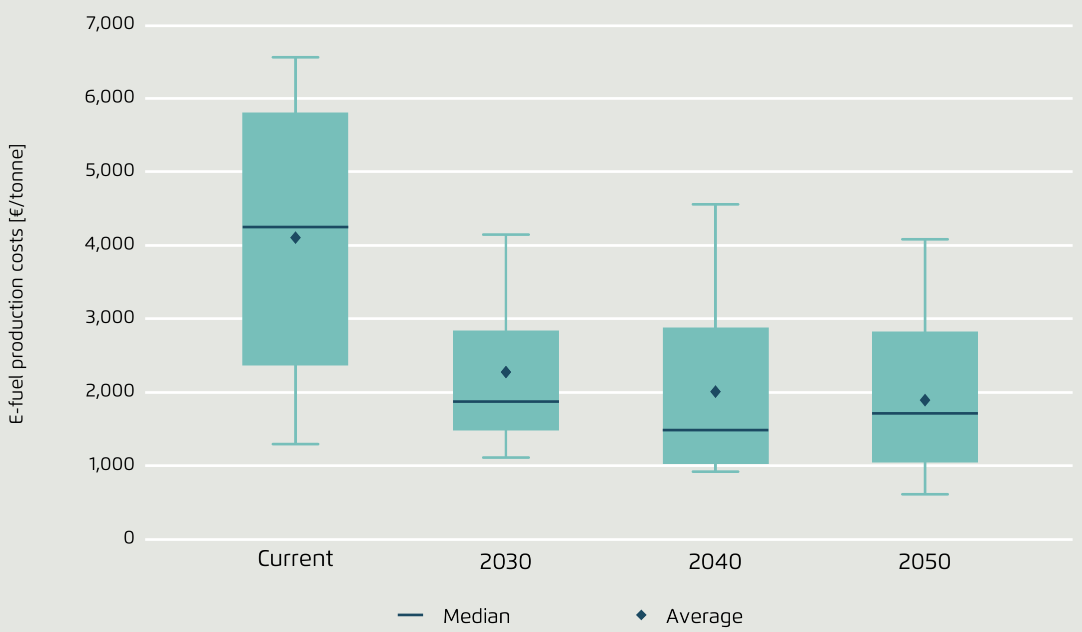
current rating of selected countries, including the basis-point spread to German government bonds, also known as "bunds".

While most e-SAF projects are funded in a hard currency (euros or US dollars) the risk premium for financing a project in a developing country can be significant. Various mechanisms have been explored to overcome this cost of capital disadvantage and enable green investment in developing countries, including guarantees, grants, and concessional loans provided by multilateral development banks (MDBs) and development finance institutions (DFIs).

Since no commercial e-fuel production plants are yet in operation, there are also no reliable figures for market prices or future costs. In recent years, various studies have sought to estimate the market costs for e-fuels. These studies generally conclude that e-fuels are four to eigth times as expensive as comparable conventional fuels. However, as is always the case with projections, these estimates are subject to considerable uncertainties.

The following figure spotlights the results of various studies on the current and future cost of e-SAF production using Fischer–Tropsch synthesis. The projections are subject to wide variation depending on the assumptions made regarding plant location, the cost of renewable electricity, and plant efficiency. On average, the estimates foresee current production costs of about 4,240 euros per tonne. However, past studies have yielded widely divergent estimates ranging from 2,440 to 5,660 euros per tonne. At the lower end of this cost range we find the studies that assume cheap renewable supply with high full-load hours, such as hydropower, in combination with CO_2 from point sources. However, in the real world, few locations can satisfy both of these factors, meaning these estimates are not reflective of the conditions that would govern large-scale production. Mid-range costs result for a combination of low-cost power with high full-load hours and an expensive CO_2 source such as DAC or, alternatively, low full-load power generation in less favourable regions with a cheaper CO_2 point source. Very high costs result when production takes place regions with low renewable potential in combination with CO_2 from DAC plants.

Hydrocarbon-based e-fuel production costs: Projected ranges including median values — Figure 15



Agora Verkehrswende and International PtX Hub (2024) | Sources: Becattini et al. (2021); BHL, LBST (2022); DECHEMA (2023); dena (2022); E4tech (2021); iea (2022); ifeu, DLR, Johaneum Research (2020); Öko-Institut (2021); Sherwin (2021); Ueckerdt et al. (2021); WEF (2020).

Looking forward, production costs are estimated to fall to 1,090 to 2,620 euros per tonne by 2050 given robust market deployment and associated learning-curve effects and economies of scale. On average, manufacturing costs in 2050 are estimated at 1,935 euros per tonne. However, such studies generally only consider "minimum" production costs. Specifically, they do not consider additional costs for fuel transportation, certification, taxes and levies, or commercial profits. In any event, the retail prices paid by airlines are likely to be significantly higher than e-SAF production costs.

Although the forecasts and estimates for e-SAF production costs vary widely, the additional macroeconomic costs that will result from their use can be estimated by considering the fuel volumes that will be required – for example, to meet the ReFuelEU Aviation RFNBO sub-quota.62 According to the aforementioned studies on e-fuel production costs, e-SAF can be produced at a cost of about 1,900 euros per tonne in 2030. Assuming current prices for fossil-based Jet A-1 of around 850 euros per tonne, this would result in additional costs of at least 1,000 euros per tonne for e-SAF. Thus, to supply the approximately 570,000 metric tons of e-kerosene required to meet the 2030 quota of 1.2 percent, additional costs of over 570 million euros would be incurred. However, when compared to the overall jet fuel supply cost of roughly 40 billion euros in the EU, this is a comparably small amount.

As a rule of thumb, the expected costs increase with the complexity of the production process and the feedstocks required in addition to hydrogen. Thus, e-methanol promises to be the cheapest option with a view to ease of production up to e-SAF. The Fischer–Tropsch route might lead to slightly higher costs, but is also a very compelling technical option, as it currently represents the only certified pathway for producing e-SAF. Furthermore, its by-products can be sold, which improves its cost effectiveness. However, this is also true for e-methanol as intermediate product when following the MtJ pathway. Indeed, e-SAF production costs are expected to fall considerably in coming years due to economies of scale, standardization, and learning-curve effects.

Ultimately it is important to stress that no hard data are available concerning the costs that will result for e-fuel production. The unit costs achieved by pilot plants are not representative of the costs achievable under large-scale deployment. Accordingly, unit cost expectations over the near term should not be the decisive factor for vanguard investments that seek to further develop e-fuel technology, given the cost efficiencies that will naturally result during a large-scale production ramp-up.

62 For additional background on this quota, please see the following section on e-fuel policies.

6 | Existing policy instruments and ambition

Various regulations at the national and international levels have been adopted with the goal of increasing the share of renewable energy in transport. Within the EU, one of the main instruments for promoting PtX fuels is the RED. In addition, various measures are being finalized or have already been adopted as part of the"Fit for 55" package, which aims to advance the European Green Deal. This package includes specific regulations to support the ramp-up of e-fuels – particularly in aviation (ReFuelEU Aviation) and in maritime shipping (FuelEU Maritime). Yet beyond Europe's borders, various nations have been adopting strategies and policies that foresee a reliance on PtX fuels . Accordingly, as part of our research, we have surveyed international developments in the area of policy designed to encourage e-SAF production and use. Specifically, in addition to considering activities being undertaken by the UN's International Civil Aviation Organization (ICAO), we analyze policy developments in two jurisdictions with high fossil fuel demand (the USA and EU); in three countries with announced ambitions to become major e-fuel demand centres (Germany, Japan, and the UK); and in three countries with rapidly rising fuel consumption and beneficial conditions for e-SAF production (Brazil, India, and South Africa).[63]

6.1 United Nations ICAO

The ICAO Global Framework for SAF, LCAF and other Aviation Cleaner Energies

At the end of 2023, the International Civil Aviation Organization (ICAO) adopted a global framework to promote SAF production and uptake. The goal of this framework is to achieve a 5% reduction in the carbon intensity of aviation fuels by 2030, in part through reliance on SAF. It acknowledges that certain states have a capacity to proceed at a faster pace than others. In addition, it encourages states to harmonize regulatory frameworks, to support SAF initiatives, and to improve financing access for SAF production, all while "leaving no country behind".[64] The ICAO framework marks an important step in the effort to ramp up SAF, as it is the first global agreement of its kind.

Carbon Offsetting and Reduction for International Aviation (CORSIA)

In 2016, ICAO adopted CORSIA (Carbon Offsetting and Reduction for International Aviation) is a market-based mechanism for reducing aviation emissions. The stated goal of CORSIA is to stabilize net emissions from international aviation at 2020 levels. Accordingly, its primary focus is to offset emissions generated by international aviation that exceed 2019 levels. In the context of CORSIA, this offsetting can be achieved by one actor paying another to reduce its emissions. From an climate science perspective, such offsets are considered to be a very weak instrument for emission reductions, as their actual effectiveness is difficult to verify.[65] CORSIA also allows airlines to achieve emission reduction targets by using alternative fuels. However, as these fuels are significantly more expensive that the CO_2 certificates from offsetting measures, CORSIA is generally not seen as an instrument with a strong potential to support SAF market ramp-up. In general, experts have raised doubts concerning the effectiveness of CORSIA, due to its weak targets and focus on offsets.

6.2 European Union

European Emissions Trading Scheme (EU ETS)

The aviation sector was partially integrated into the European Emissions Trading Scheme (EU ETS) in 2012. Since then, airlines have been required to purchase emission certificates for all flights within the European Economic Area (EEA) as well as from the EEA to Switzerland or the United Kingdom. In May 2023, the rules in this regard were extended to 2027; international flights outside of the EEA will only be covered under CORSIA, and not under the ETS.[66] In 2026, however, the Commission will review whether CORSIA is sufficient for

63 The policy information presented herein is based on desktop research, which considered public policy databases maintained by the IEA (2023a) and New Climate Institute (2024), primary resources available at government agency websites, and secondary news sources. In order to verify and enrich the retrieved data, we also carried out expert interviews with representatives from domestic think tanks and private companies.

64 ICAO (2023).

65 T&E (2022c).

66 European Parliament and Council of the European Union (2023a).

meeting the targets of the Paris Agreement. In the event of a negative decision, the Commission may extent ETS to cover international flights. To date, airlines have been allocated a large share of free allowances. However, the allocation of free allowances will be gradually reduced between 2024 and 2026. Furthermore, from 2025 onwards, airlines will be required to record and report non-CO_2 effects, which account for around two-thirds of the total climate impact of aviation. This represents a major change. Furthermore, by 2028 legislators will draw up a draft law on the pricing of these emissions in the ETS.[67] Instead of offsetting emission through the purchase of additional allowances, airlines have the option of expanding their reliance on SAF, as the ETS considers SAF to be carbon-neutal. Accordingly, future carbon prices in combination with SAF exemption could an important driver of SAF production and use.[68]

ReFuelEU Aviation

Another important measure in the Commission's Fit for 55 package is the ReFuelEU Aviation directive, which aims to reduce emissions in aviation.[69] The directive, which entered into force in October 2023, prescribes specific blending quotas for sustainable aviation fuels (SAF) and sub-quotas for "synthetic aviation fuel", including RFNBOs (i. e. e-SAF and hydrogen). The share of these fuels in the aviation sector will be increased from 2% in 2025 to 70% in 2050 (see Figure 16). The RFNBO sub-quota will start at 1.2% in 2030, will increase to 2% in 2032, and will reach 35% by 2050.

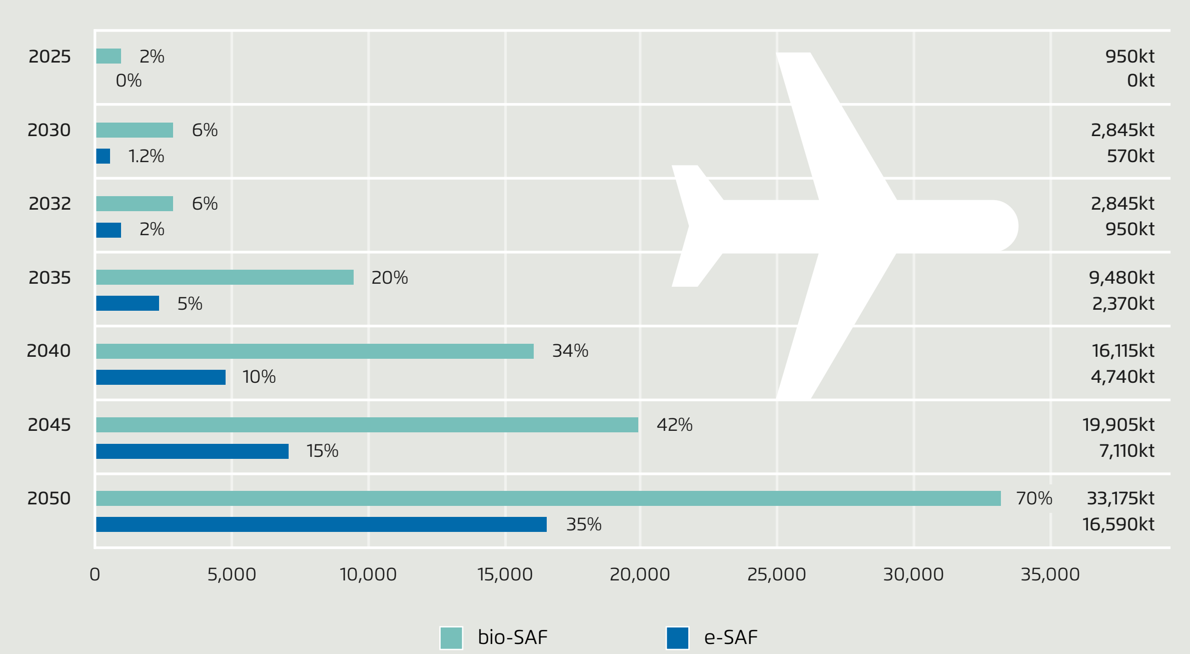
The directive will require flights departing from airports within the EU to be sustainably fuelled, in order to avoid strategic refuelling outside the EU (so-called "tankering"). Specifically, the directive requires the annual quantity of

67 Euractiv (2023).

68 For further information on the interrelationship between EU ETS and RefuelEU Aviation, please see Öko-Institut (2024).

69 European Parliament and Council of the European Union (2023b).

Development of the ReFuelEU Aviation quota for sustainable aviation fuels (SAF) Figure 16



Agora Verkehrswende and International PtX Hub (2024) | Note: Based on a 2019 kerosene consumption of roughly 47.4 Mio. t within the EU; assumed LHV: 43 MJ/kg. Source: Kerosene consumption based on iea (2024).

aviation fuel uplifted at a given EU airport to be at least 90% of the annual aviation fuel required. Over the long-term, the quotas will apply to all EU airports. However, during a transitional period up to 2034, fuel suppliers will be allowed to fulfill the blending mandate as a weighted average within the EU (i. e. such that some airports are supplied with higher SAF amounts, while others are sup-plied with lower amounts). Recent clarifications provided by the European Commission indicate that this flexibility mechanism will apply at the member state level, implying that the quota has to be fulfilled as a weighted average at EU airports within each member state.

German PtL-SAF quota

Prior to the discussion of an SAF quota at the European level as part of the ReFuelEU Aviation inititive, Germany introduced a sub-quota for electricity-based fuels in aviation (e-kerosene). This quota dictates a 0.5% e-kero-sene share in total kerosene sales in Germany from 2026 onwards (corresponding to a market volume of approx-imately 50,000 tonnes), and is set to increase to 2.0% in 2030. This e-kerosene mandate only imposes obligations on the distributors of kerosene and is thus separate from the general GHG reduction quota in Germany (which is based on the national implementation of the EU RED).[70]

Accordingly, the German PtL quota is more ambituous than the ReFuelEU Aviation targets. As of April 2024, the reconciliation of these targets remains to be clarified.

6.3 United States of America

In 2021 the US Departments of Energy, Transportation, and Agriculture launched the SAF Grand Challenge, building on the US 2021 Aviation Climate Plan, which aims to achieve net-zero emissions from US aviation by 2050.[71] The SAF Grand Challenge seeks to incease the production and utilization of SAF while also reduc-ing costs and enhancing sustainability. The associated roadmap, which requires SAF to reduce emissions by at least 50% on a life-cycle basis compared to conventional jet fuel, foresees the annual production of 3 billion gallons (11.3 billion liters) of SAF by 2030. Production is to be increased to 35 billion gallons (132.4 billion liters) by 2050, thus meeting 100% of aviation fuel demand in that year.

The US policy approach relies at present on economic incentives. The Inflation Reduction Act (IRA) provides for grants worth some $244.5 million for investment projects dedicated to SAF production, transportation, blending, or storage until September 2026.[72] To qualify, the SAF need to meet the mentioned 50% GHG emission reduction threshold and be derived from biomass, waste streams, renewable energy, or gaseous carbon oxides. In addition, the US has established tax credits which begin at $1.25 per gallon ($0.33 per liter) of SAF and rise incrementally for each percentage point improvement in life cycle emissions performance to a maximum of $1.75 per gallon ($0.46 per liter).[73]

The US Renewable Fuels Standard requires transpor-tation fuel sold in the US to contain a certain minimum volume of "renewable fuel".[74] The SAF Grand Challenge Roadmap highlights the need to interlink the Renewa-ble Fuels Standard with the IRA. However, as of January 2024, no plans have been announced for specific SAF or e-SAF blending mandates.

6.4 United Kingdom

In April of 2024 the UK government published the details of its SAF mandate, which is set to enter into force in 2025 and require at least 10% of jet fuel to be made from sustainable feedstocks by 2030 (as part of the broader goal of achieving climate neutral aviation by 2050).[75] Notably, the SAF mandate will operate separately from the Renewable Transport Fuel Obligation (RTFO), which mandates fuel suppliers to provide a certain percent-age of renewable fuel.[76] At present, SAF suppliers can receive compensation under the RTFO scheme, as SAF is considered a 'development fuel' (i. e. RFNBO or bio-based

70 Bundesministerium für Digitales und Verkehr (2021).
71 United States Department of Energy (2022).
72 The White House (2023).
73 Internal Revenue Service (2023)
74 A term that as of now only includes conventional biofuels, and advanced biofuels (e. g. from sugar cane), and bio-mass-based diesel (e. g. from waste oil); see Environmental Protection Agency (2022).
75 Department for Transport (2024).
76 Department for Transport (2023).

from waste or residue). The announced SAF mandate will incorporate tradeable certificates for producers, which will be awarded in proportion to the GHG-savings achieved, thus incentivizing the production of cleaner fuels. Eligible fuels encompass waste and residue-derived biofuels, recycled carbon fuels (RCFs), and Power-to-Liquid (PtL) fuels. SAF under this mandate must achieve a minimum of 40% GHG-savings compared to fossil jet fuel (53.4 g CO_2e/MJ or 2.3 kg CO_2e/kg jet fuel). This threshold may become more strigent in future revisions of the policy. Additionally, there will be a cap on SAF derived from HEFA, and a "PtL" obligation for "low carbon aviation fuels" will be introduced. The HEFA cap is meant to incentivize usage of a wider range of feedstocks, particularly hydrogen. It is acknowledged that a PtL sub-mandate is needed to ensure a faster ramp-up of this technology, as it promises high GHG savings, despite low risk of land-use changes. The PtL mandate will start at 0.2% in 2028 and increase to 3.5% by 2040. The draft bill still has to be approved by the UK parliament.

The UK Emission Trading System (UK ETS) covers domestic aviation, flights between the UK and Gibraltar, and flights departing from the UK to the European Economic Area.[77] The UK ETS, like the EU ETS, aims to address GHG-emissions by implementing a cap-and-trade system. Starting 1 January 2021, the limit for Phase 1 of the UK ETS was established at 5% below the anticipated notional allocation for the EU ETS Phase IV (2021–2030). This cap persisted until the conclusion of phase 1 in 2023, after which a new 'net-zero cap' was implemented. In July 2023 the UK ETS Authority declared its intention to discontinue free allocations for aviation by 2026. Instead, aviation companies will be required to purchase allowances for each tonne of carbon emitted within the scheme. To ensure aircraft operators are able to prepare for the upcoming change, the aviation free allocation entitlement will continue to reduce at the established fixed rate of 2.2% annually in both 2024 and 2025, leading to complete auctioning by 2026. Furthermore, the authority states that a proposal will be formulated on how to treat SAF based on the newly established SAF mandate criteria within the UK ETS and on how non-CO_2 impacts can be included.

77 United Kingdom Department for Energy Security and Net Zero (2023).

6.5 Japan

Japan's Basic Hydrogen Strategy has a variety of goals: by the 2030s, Japan aims to develop demonstration aircraft; showcase manufacturing technology for sustainable aviation fuels (SAFs), including synthetic fuel (e-fuel); expand utilization with fuel-efficient technologies and advanced materials in aviation; and enhance flight operations.[78] The 2023 revision of the Basic Hydrogen Strategy includes the 2030 target of replacing 10% of aviation fuel sold by fuel distributors with SAF in international flights. Previously, in 2022, the government revised the Civil Aeronautics Law, commissioning the Ministry of Land, Infrastructure, Transport, and Tourism to develop a Basic Policy to Promote Decarbonization in Aviation. The concrete proposal, presented in October of 2022, includes a 2030 CO_2 reduction target of 16% for domestic flights and also envisions climate neutrality by 2050 for both domestic and international flights.[79] To achieve these targets, SAF is cited as a crucial mitigation option. The Basic Hydrogen Strategy states the intent of finalizing the Basic Policy for Promoting Decarbonization of Aviation. Crucially, however, a regulatory definition of SAF remains outstanding.

Japan recently announced plans to introduce a carbon levy on fossil fuel importers beginning in 2028, initially at an affordable level but gradually increasing on an annual basis. In addition, an Emission Trading Scheme (GX ETS) will be phased in for high-emission sectors, starting with voluntary trading among the GX League (a group of Japanese companies). From 2033 onwards allowances will be auctioned to electric power companies to expedite the decarbonization of the power sector. The Japanese aviation sector will likely be affected by the carbon fuel levy.[80]

6.6 Brazil

In Brazil, the Fuel of the Future Program, which was tabled in September 2023, foresees the introduction of CO_2 reduction targets for airlines in their domestic

78 Ministry of Economy, Trade and Industry (2023).

79 Ministry of Land, Infrastructure, Transport and Tourism (2022).

80 Agency for Natural Resources and Energy (2023)

operations, rather than blending mandates; international flights will be exempt.[81] The reduction obligations will start at 1% in 2027 and increase progressively to 10% in 2037. The reference year for emissions is not specifically mentioned, but given the policy's orientation to the CORSIA scheme, average emissions in 2019–20 are likely to be the baseline.

The obligations must be met through the consumption of SAF, and not via technological or operational improvements. A legal framework for SAF is included in the bill and supplemented with specifications regarding "aviation biokerosene". Here, the term "bio" does not mean "limited to biogenic", but rather denotes "alternative to fossil". This becomes evident through the details of the bill, which state all technological routes for the production of SAF are allowed as long as they are approved by the American Society for Testing and Materials (ASTM) (thus paving the way for e-SAF compliance with production based on Fischer–Tropsch synthesis).

81 Ministry of Mines and Energy (2023).

6.7 India

In India's National Green Hydrogen Mission, aviation is mentioned as a sector in which pilot projects are to be undertaken over the medium term (Phase II, 2026–2030).82 In November 2023, India announced the goal of achieving a 1% SAF blending ratio for jet fuel by 2027, and of achieving a 2% ratio by 2028. Initially, these targets will apply to international flights.[83] However, as of December 2023, no regulatory framework for the mandatory application of SAF in the aviation sector had been published. It can be assumed that this quota will initially seek to introduce biofuels in aviation, not least given the lack of a regulatory definition of hydrogen derived fuels.

6.8 South Africa

The South African Green Hydrogen Commercialization Strategy foresees expediting private investment in aviation fuel, green methanol, and green ammonia projects

82 Ministry of New and Renewable Energy (2023).
83 Reuters (2023).

Overview of policies in place of relevance to e-SAF ramp-up in the transport sector in selected jurisdictions — Table 4

	Framework for sustainable e-SAF production	Blending mandate for e-SAF that applies to fuel suppliers	Carbon pricing mechanism that includes aviation	Binding CO_2 emission reduction obligations for aircraft operators
ICAO	Yellow	Grey	Green (a)	Grey
European Union	Green	Green	Green	Grey
Germany	Green	Green	Green	Grey
USA	Grey	Grey	Grey	Grey
UK	Green	Yellow	Green	Grey
Japan	Grey	Grey	Yellow	Grey
Brazil	Grey	Grey	Grey	Yellow
India	Grey	Grey	Grey	Grey
South Africa	Grey	Grey	Green	Grey

Green: In force Yellow: Planned Grey: Not yet addressed
a In contrast to other pricing mechanisms such as the EU ETS, the ICAO scheme CORSIA focuses on offset certificates to be purchased by aircraft operators for their emissions rather than (capped) CO_2 allowances (for further information, please refer to section 6.1).

Agora Verkehrswende (2024) | Source: Government documents of the countries listed. Information current to June 2024.

as a means of supporting local value creation.[84] A carbon fuel levy applies to fuel suppliers. The levy amount is scheduled to rise incrementally on an annual basis, from $20/t in 2025 up to a minimum of $30/t by 2030.[85] Furthermore, beginning 2026, the carbon tax is expected to experience more substantial yearly increases. An even further increase in the carbon fuel levy, as proposed by the Green Hydrogen Commercialization Strategy, could incentivize the introduction of less carbon-intensive fuels such as e-SAF. However, as of December 2023, no regulatory framework for SAF has been published (this is prerequisite for clarity concerning carbon tax exemption). Furthermore, there are no official plans for establishing SAF blending mandates in South Africa.

84 Department of Trade, Industry and Competition (2023).

85 National Treasury (2010).

7 | E-SAF demand and availability

E-SAF production levels in the coming years are difficult to forecast. In relaton to the current worldwide offtake of fossil jet fuel (370 million tonnes per year[86]), actual SAF offtake is in the per mille range (see Figure 17), and is largely covered by bio-SAF. At present, just a few plants produce e-fuels, and the number of new facilities under construction is very low. While various projects with large production capacities have been announced, most of these projects are at an early stage (e. g. general feasibility study; basic engineering; final investment decision made). Nevertheless, various regulatory measures are in place to ensure a market ramp-up of e-fuels, especially on the demand side, in order to achieve climate protection goals. Specifically, as discussed in the prior section, the EU has adopted quota obligations for the use of e-fuels in air and sea transport. Furthermore, numerous countries have enacted CO_2 reduction obligations for fuel suppliers and manufacturers, as well as market-based measures such as carbon pricing systems. Last but not least, various jurisdictions have targeted incentives to support the development of the e-fuel market (such as the tax breaks and subsidies provided under the IRA).

Despite the attendant uncertainties, e-fuel production levels up to 2030 can be roughly estimated based on current project announcements and other public data. Some three to four years are required for the design, permitting, and construction of an e-fuel plant.[87] Accordingly, only few projects that foresee completion after 2030 have been announced to date.

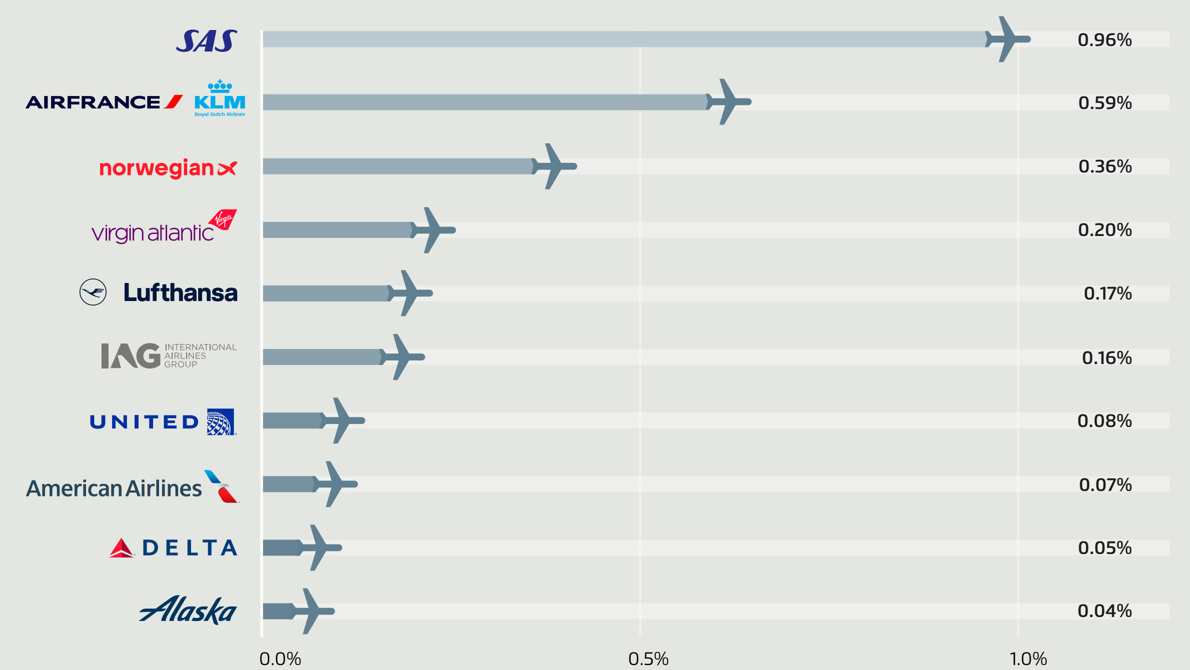
In the following, the future demand and availability of e-SAF will be discussed. We consider forecasts by various studies for the achievement of climate neutrality goals, as well as demand arising from existing quota obligations. We then compare this demand with announced projects to produce e-SAF via the Fischer–Tropsch and

86 Original data: 7,971 thousand bbl/d; assumed jet fuel density: 0.8 kg/l; see BP (2022).

87 This may even take longer for first-of-its-kind projects, especially when it comes to engineering and approval processes.

SAF share by commercial passenger airlines remains low

Figure 17



Agora Verkehrswende and International PtX Hub (2024) | Note: SAF as a share of all jet fuel in 2022. Source: Bloomberg (2023).

methanol route, and estimate the land area and energy demand required to produce sufficient e-SAF to completely substitute current jet fuel demand.

7.1 Forecasting future e-SAF demand

The table below presents forecasts regarding future e-SAF demand in the European Union andglobally. As is evident from the table, these forecasts diverge considerably. In the studies presented for the European Union, the figures for 2030 can be subdivided into two groups: two studies see very low demand (well below 1 million tonnes) while three studies envision much higher consumption levels. The ICCT forecast stands out, as it estimates e-fuel production at just 0.2 million tonnes (however, it only takes production potential within the EU into account). A study conducted by the European Union Aviation Safety Agency (EASA), which presumes fulfillment of the RefuelEU Aviation quotas, results in a slightly higher demand of 0.3 million tonnes. By contrast, the more optimistic scenarios envision higher demand between 1.3 million and 1.9 million tonnes, which corresponds to 3 to 4 percent of total jet fuel demand in 2019 (when demand stood at 47 million tonnes). While these higher figures for 2030 seem to be quite optimistic, the scenario figures for 2050 are even more divergent, with some scenarios seeing

Overview of selected studies forecasting the e-SAF demand based on different climate protection and market scenarios. Table 5

	2030			2050		
	Million tonnes	Billion litres	Petajoule	Million tonnes	Billion litres	Petajoule
European Union						
EASA[1]	0.3	0.4	12.9	12.7	15.9	546.1
ICCT[2]	0.2	0.2	6.5			
Öko-Institut/T&E[3]	1.9	2.3	80	39.2	49	1,685.6
Ricardo/T&E[4]	1.4	1.8	61.6	28	35	1,206.9
T&E[5]	1.3	1.7	57.6	24.7	30.9	1,062.1
Global						
BP[6]	0.6	0.8	25.8	67.7	84.6	2,911.1
dena[7]	63.8	79.8	2,743.4	303.3	379.2	13,043.2
ICAO[8]	5.0	6.3	215	54.9	68.2	1,685.6
IEA[9]	3.5	4.4	150.5	129.1	161.4	5,551.3

1 EU-wide climate neutrality by 2050; implementation of the e-fuels quotas from ReFuelEU Aviation (shown here); EASA (2022).
2 Availability of sustainable raw materials for the production of SAF in the European Union; the e-fuels share is shown here; ICCT (2021).
3 Defossilisation of aviation in Europe by 2050; the e-fuels share is shown here; Öko-Institut (2021).
4 Decarbonization of European transport by 2050 with a higher share of e-fuels (shown here). Data based on required electricity in TWh (2030: 38 TWh; 2050: 745 TWh). Assumptions for conversion to e-SAF: Efficiency factor for e-SAF production via FT route: 45%; kWh/kg SAF = 11.94 (LHV); kWh/L SAF = 9.56 (LHV); Ricardo (2020).
5 Climate-neutral aviation in Europe by 2050; the share of e-fuels is shown here; T&E (2022a).
6 Net Zero scenario, share of hydrogen-derived fuels for aviation based on low-carbon hydrogen projections; BP (2023).
7 97% of jet fuel demand covered by e-SAF;dena (2022).
8 Total jet fuel demand covered with SAF; the e-SAF share with DAC and high traffic volume is shown here; ICAO (2022b).
9 Scenario for achieving 1.5°C goal, includes all synthetic hydrogen-based fuels; IEA (2023a).

Agora Verkehrswende (2024)

65 to 95 percent of the jet fuel demand being covered by e-SAF (31 to 45 million tonnes), and others envisioning a demand share of 27 to 53 percent (corresponding to 13 and 25 million tonnes, repectively). No scenario foresees complete coverage of 2050 jet fuel demand with e-SAF.

Taking a broader view, the German Energy Agency (dena) has estimated the quantities of e-SAF that would be required to cover nearly all of global jet fuel demand, arriving at a figure of 300 million tonnes for 2050. For its part, ICAO foresees the share of e-SAF produced with CO_2 from direct air capture (DAC) in a scenario that presumes a high volume of aviation traffic at around 55 million tonnes in 2050. Biofuels play a larger role in this scenario. BP predicts production of hydrogen-based energy sources at around 68 million tonnes in 2050 in its "Net Zero" scenario. By contrast, a recent IEA scenario for delivering on the 1.5°C target has estimated global e-SAF production in 2050 at 129 million tonnes (this figure lies roughly in the middle of the range established by the dena and ICAO estimates).

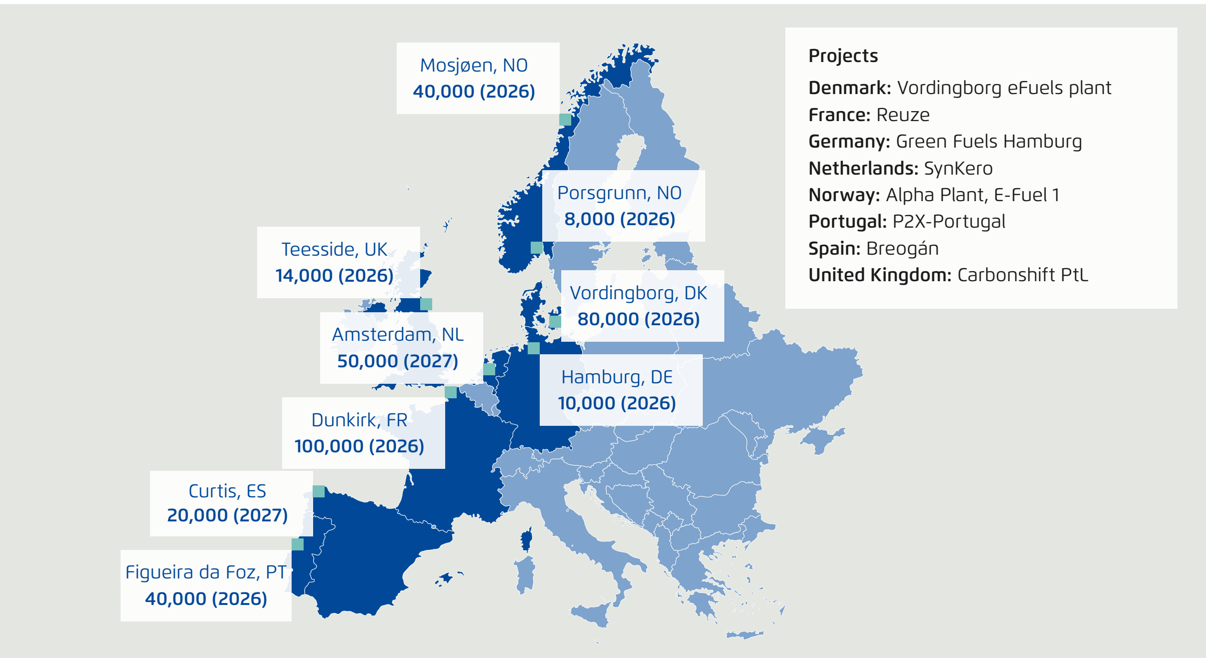
7.2 Announced e-SAF production

Nearly all Fischer–Tropsch plants for the production of e-fuels (whether announced or in operation) are geared to the production of sustainable aviation fuel and thus to maximize e-kerosene yield. E-naphtha (raw gasoline) and e-diesel are still produced as secondary products. If further processing takes place directly in the e-fuel plant, the e-kerosene content can be between 50% and 70% – and is expected to rise to 80% in future with improvements to process design, operating conditions and catalysts.[88]

While no significant production capacities for e-SAF exist at present, large-scale industrial plants are in various stages of planning. To date, only three smaller demonstration plants have been built: In Werlte, Germany, Atmosfair operates a plant that primarily produces e-kerosene for further co-processing to jet fuel, and in Hamburg, Germany, P2X Europe operates a plant

88 Schär (2022).

Overview of industrial e-SAF projects with planned start-up by 2027 — Figure 18



Agora Verkehrswende and International PtX Hub (2024) | Note: Total planned capacity in t/a based on public announcements as of March 2024; the year refers to announced commissioning or expansion. References in appendix.

that primarily produces e-diesel and e-waxes for the chemicals industry. These plants each have a production capacity of around 350 tonnes per year. Lastly, at the beginning of 2024 an e-SAF plant built and operated by Infinium went into operation in Texas. The first industrial plants are scheduled to come on line between 2025 and 2027 and are being developed mainly in Europe (see Figure 18).

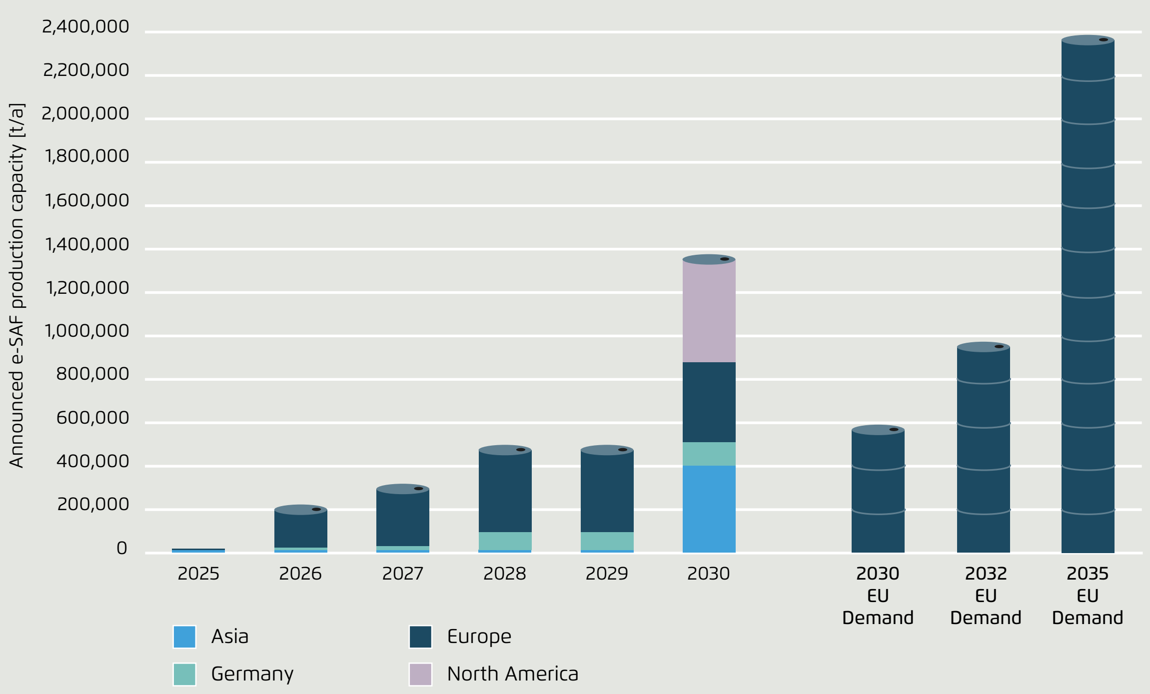
However, due primarily to uncertainties surrounding EU regulatory provisions, including the sustainability criteria for green hydrogen contained in RED II (Delegated Acts on Articles 27 and 28), final investment decisions for these plants are still largely pending.[89] The first significant quantities of e-SAF could be produced as early as 2026 if the announced plants are realized on schedule (see Figure 19). Cumulative global production capacity would then amount to about 200,000 tonnes per year.

89 T&E (2024); Ueckerdt, Odenweller (2023).

In the following years, further plants with an additional production capacity of roughly 270,000 tonnes per year could in all likelihood come on line, followed by further large plants that are scheduled to go into operation in 2030. This could lead to a maximum expected e-SAF production capacity of around 1,360,000 tonnes per year. Depending on the final process layout and associated product spectrum, additional amounts of naphtha and diesel may be produced, which could be used as feedstock in the chemicals industry or as a transport fuel (e.g. in shipping). However, since hardly any of these projects are currently under construction, commissioning prior to 2030 to contribute to the EU quota obligations is unlikely.

Compared to e-SAF, considerably larger production capacities have already been announced for e-methanol. This is partly attributable to easier process management, mainly due to fewer and simpler conversion steps, and the wide range of applications for methanol. Under

Anticipated global e-SAF production capacity up to 2030 and ReFuelEU Aviation demand — Figure 19



Agora Verkehrswende and International PtX Hub (2024) | Note: Authors' projection based on public announcements, data in appendix; where no kerosene production figures were available, a 60% product split was assumed for Fischer-Tropsch projects.

current market conditions, methanol can be used flexibly as a raw material in the chemicals industry; as a fuel additive or substitute (e.g. in shipping); or can be further processed into drop-in fuels such as e-gasoline (MtG, methanol-to-gasoline process) or e-SAF (MtJ, methanol-to-jet process). According to current announcements, several plants with varying production capacities (from 10,000 to 1 million tonnes per year) are slated to go into operation in the coming years. As Figure 20 shows, these plants should collectively produce some 2.7 million tonnes of e-methanol by 2027. Just over half of this capacity will come from a single plant planned by HIF global in the USA, scheduled to produce 1.4 million tonnes by 2027.[90] At least some of the methanol produced by these plants could directly be processed into jet fuel on site. As the certification process for e-SAF produced from methanol is still pending, only few projects announced to use this production route. However, this includes two of the biggest so far announced e-SAF production plants with a combined production capacity of nearly 1 million tonnes in 2030.

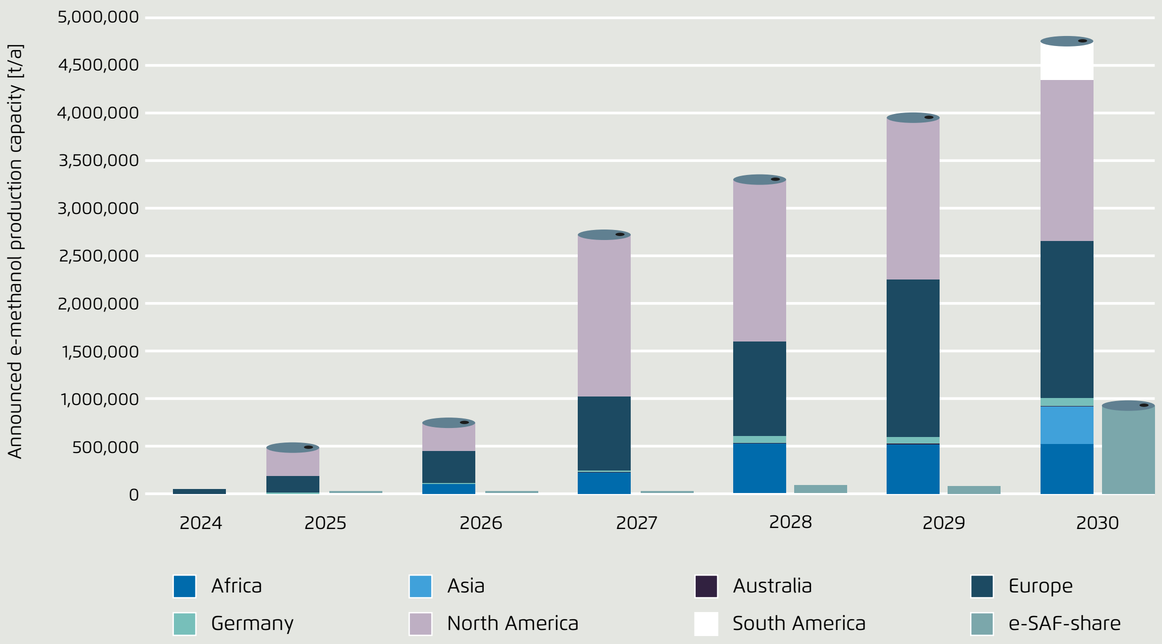
90 Cision PR Newswire (2022b).

7.3 European e-SAF demand

The Europe-wide RFNBO sub-quota implemented within the ReFuelEU Aviation regulation will by itself create demand that would consume most of the foreseeable global e-SAF production. As early as 2030, fulfilling the EU obligation will generate demand for some 570,000 tonnes of e-SAF (1.2% of EU jet fuel demand), almost half of the announced worldwide production capacity (i.e. solely fuel produced via Fischer-Tropsch synthesis as long as e-SAF produced from methanol is not yet approved for commercial applications). This demand will increase to 950,000 metric tons in 2032 and rise to 2.4 million metric tons in 2035 (representing 2% and 5% of EU jet fuel demand, respectively). The required production capacity will only be achieved if e-SAF from

Anticipated global e-methanol production capacity up to 2030 and the e-SAF share produced from methanol

Figure 20



Agora Verkehrswende and International PtX Hub (2024) | Note: Authors' projection based on public announcements, data in appendix.

MtJ routes is included in the respective ASTM standards by that time. For Europe alone, this would require significantly larger production capacities than currently planned. By comparison, EU jet fuel consumption represents only about 14%of global consumption.[91] Therefore, an even more ambitious market ramp-up for e-SAF is necessary. These back-of-the-envelope calculations show that ambitious quotas have not been sufficient to trigger a sufficiently large production ramp-up. Accordingly, there is a clear need for supplemental supply-side measures.

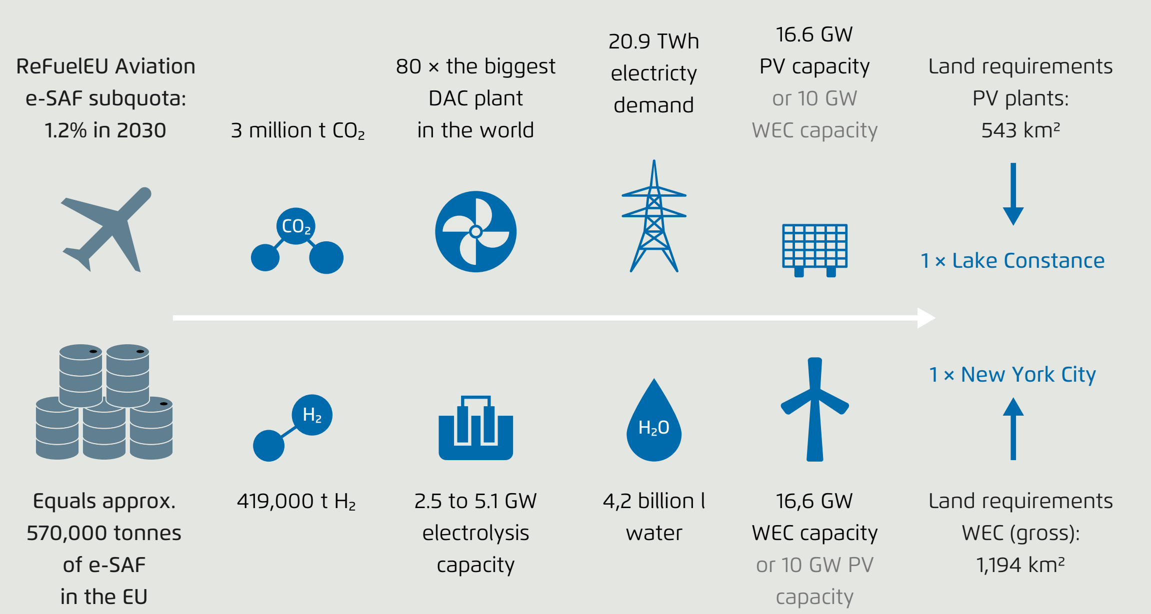
Meeting future quota-based e-SAF demand needs will require not just the construction of the synthesis plants but also an ample supply of renewable electricity, sustainable sources of carbon, and electrolyzers for hydrogen production. Since renewable electricity will be a scarce resource over the coming decades as policymakers move to decarbonize all sectors of the economy, the electricity needed for e-fuel production should come from additionally installed renewables capacity that is expressly built to cover the power needs of e-fuel production.

In concrete terms, this means that if the volumes required to meet the ReFuelEU Aviation subquota were to be produced in the EU, additional electrolysis capacities of 2.5 to 5.1 gigawatts would be needed (see Figure 21). Furthermore, fulfilling the 2035 quota would necessitate 10.5 to 21.1 gigawatts.[92] By comparison, global installed electrolysis capacity stood at approximately 0.7 gigawatts

91 Kerosene consumption in 2019 (pre-pandemic levels) – EU: 47.39 million tonnes, worldwide: 331.56 tonnes (U.S. Energy Information Administration, 2023).

92 The range results from the assumed full load hours of the electrolysers (4,000 to 8,000 hours per year); required storage capacities were not taken into account, as these would mainly be reflected in the production costs.

Estimating the energy, material and land requirements to fulfill the EU e-SAF quota obligation in case of full supply from Central Europe — Figure 21



Agora Verkehrswende and International PtX Hub (2024) | Note: Authors' projection, data in appendix; DAC = direct air capture, WEC = wind energy converter.

at the end of 2022 and was anticipated to have tripled to 2 gigawatts by the end of 2023.[93] Although a rapid ramp-up of electrolysis capacity is expected, announced projects primarily aim to decarbonize industry (e. g. steel andchemicals, including fertilizers). The EU's hydrogen strategy, which aims to install 40 GW electrolyzer capacity by 2030, is also focused on these areas of application.[94]

A total of roughly 21 terawatt hours of renewable electricity would be needed to produce sufficient e-SAF. If the renewable electricity required in this regard were to be generated exclusively by photovoltaic systems in Central Europe, around 16.6 gigawatts of additional capacity would have to be installed. This corresponds to roughly ten percent of current aggregate PV capacity in Europe. The installation of this capacity would require fairly significant land resources; for ground-mounted PV, some 543 square kilometers (200 square miles) would be needed – roughly the area of Lake Constance.

Alternatively, the required electricity could also be generated by onshore wind turbines. In this case, additional wind turbines with a capacity of around 10 gigawatts would have to be newly built. This corresponds to approximately 2% of the EU target for installed wind energy capacity in 2030. The land area required for these turbines would only amount to 12 square kilometres (if the turbines were constructed right alongside one another). However, in order to avoid wind wake effects, turbines must be spread out over a significant area. Wind turbines with a combined capacity of 10 GW would need to be distributed over some 1,200 square kilometres (460 square miles), which is roughly the area of New York City.

The additional PV or wind capacity that is required to produce a given volume of e-fuels would be correspondingly lower in "sweet spot" regions with high full load hours. Yet even if e-fuel production capacity were developed in favourable regions outside of Europe, with the goal of producing e-fuels for import to the EU, enormous renewable generation and fuel production capacities would be required.

In addition to an ample supply of renewable electricity, which, as discussed, places demand on land resources, sustainable CO_2 is required as a feedstock. To meet the aforementioned RFNBO quota in 2030 with e-SAF, about three million tonnes of CO_2 would be necessary per year, which would have to be provided either from the air or from biogenic sources to realize a closed CO_2 cycle. By comparison, the largest DAC plant operating in the world can capture up to 36,000 tonnes per year from the air when fully operational. Accordingly, if all plants were of this size, more than 80 such plants would need to be in operation by 2030.[95]

Fossil CO_2 from industrial point sources may be used until 2035 (and in certain cases until 2040) while still fulfilling EU RED sustainability requirements.[96] Thus, a short-term plant ramp-up could be achieved with low-cost CO_2. However, additional fossil CO_2 would continue to be emitted when the e-fuels are used. In order to ensure these plans are able to produce CO_2-neutral e-fuels in the future, readiness for conversion to direct air capture should be taken into account during the plant design phase.

In addition to aviation fuels, the synthesis process produces e-diesel and e-naphtha (also known as raw gasoline), an important feedstock in the chemicals industry and a precursor to gasoline. Thus, depending on the actual Fischer–Tropsch refinery design, in addition to the 570,000 metric tonnes of e-kerosene needed to meet the ReFuelEU RFNBO quota, about 100,000 metric tonnes of e-naphtha (corresponding to about 0.5 percent of German gasoline sales in 2019) and 275,000 metric tons of e-diesel (about 0.8 percent of German diesel sales in 2019) would be produced. These secondary products, which are also CO_2-neutral, could be used to help defossilise the chemicals industry or other difficult-to-abate segments of the transport sector, such as shipping. Alternatively, they could be used to reduce the climate impact of the existing car and truck fleet during its transition to electric vehicles.

93 IEA (2023b).

94 European Commission (2020).

95 The currently largest plant ('Mammoth) is operated by Climeworks in Iceland and came into operation in 2024. Climeworks (2024).

96 This is mandatory for the produced e-fuels to count towards the fulfillment of EU quota obligations, even if the fuels are produced outside of the EU.

8 | The mission to defossilise aviation

As is evident from the foregoing discussion, the volume of e-SAF required to defossilise aviation is enormous. Indeed, covering just a small fraction of the demand (e. g. to meet the EU's initially low quota obligations; see section 6) will necessitate tremendous increases in e-SAF production. However, domestic production at the necessary scale is unlikely to be possible in many countries, including in particular industrialized nations with significant aviation hubs that are already reliant on energy imports. Accordingly, these nations will need to import e-SAF from "sweet spot" regions that have excellent meterological conditions for renewables as well as sufficient sustainable water resources.

However, large-scale e-SAF development will present numerous challenges, even in sweet spot regions. In addition to potentially placing stress on water resources, e-SAF production will require large-scale renewables expansion, which will bring enormous land-use requirements. Ensuring access to sufficient volumes of sustainable CO_2 is yet another hurdle to e-SAF development. Given the hopes that are often attached to e-SAF as solution for climate-neutral aviation, the following question naturally arises: What would it mean for sweet spot regions if e-SAF production was sufficiently expanded to fully defossilise the aviation sector?

Aviation consumed some 370 million tonnes of jet fuel in 2019.[97] Global jet fuel consumption significantly dropped due to the Covid pandemic, but has since returned to pre-pandemic levels. Accordingly, the 2019 figures are roughly equivalent to current consumption. While overall fuel demand is expected to decline significantly due to various factors – including increasing shares of battery electric vehicles; the broader shift to more sustainable forms of transport ("modal shift"); and demand reduction measures –in the aviation sector, fuel demand can be expected to remain elevated. While most experts project an increase in aviation traffic, efficiency improvements are also likely. Accordingly, the following estimations are based on the assumption of stable fuel demand levels looking forward.

In our scenario estimations, the annual electricity generation required for e-SAF production with Fischer-Tropsch synthesis at a scale sufficient to fully replace fossil jet fuel would be more than 13.6 petawatt hours.[98] This is roughly half the total global electricity production today (which stood at 28.8 petawatt hours in 2022).[99] If this electricity were to be produced using PV systems installed in very favorable locations, some 5.9 terrawatts of nominal power capacity would have to be newly developed. This is roughly five times the PV capacity currently installed worldwide (which stood at roughly 1.2 terrawatts in 2022).[100] The land area required for these PV systems would be equivalent to some 137,710 square kilometres (53,170 square miles). To put this into perspective: Chile is considered a particularly well-suited country to produce e-fuels, due to its favorable solar and wind conditions. If the entire e-SAF, were to be produced with electricity from PV systems in Chile, almost double the size one of Chile's largest and sparsely populated regions - the Atacama – would be needed.

The required overall capacity would be lower if onshore wind turbines were used, due to their higher full-load hours compared to PV. However, some 2.6 terrawatts of onshore capacity would nevertheless be required, tripling the current global capacity (which stood at 0.84 terawatts in 2022).[101] The area required for wind turbines is significantly larger than that for photovoltaic systems due to the required minimum distance between single turbines. Accordingly, some 315,310 square kilometers (121,742 square miles) would be required for the installation of this onshore wind capacity. This is roughly half the area of Chile (756,102 square kilometers or 291,933 square miles). However, the unused space between turbines can be dedicated to other purposes, which is why the net area requirement – i. e. the area required solely for turbines and access roads – is significantly lower, amounting to 3,155 square kilometers (1,218 square miles).

It is highly unlikely that the enormous production capacities required to defossilise aviation would be concentrated in one region of the world. Nevertheless,

97 Original data: 7,971 thousand bbl/d; assumed jet fuel density: 0.8 kg/l; BP (2022).

98 The electricity demand calculated here includes hydrogen production, DAC, and e-SAF synthesis. The boundary conditions assumed for calculating the land area and energy requirements can be viewed in the data appendix.

99 IEA (2023c).

100 Statista (2024a).

101 Statista (2024b).

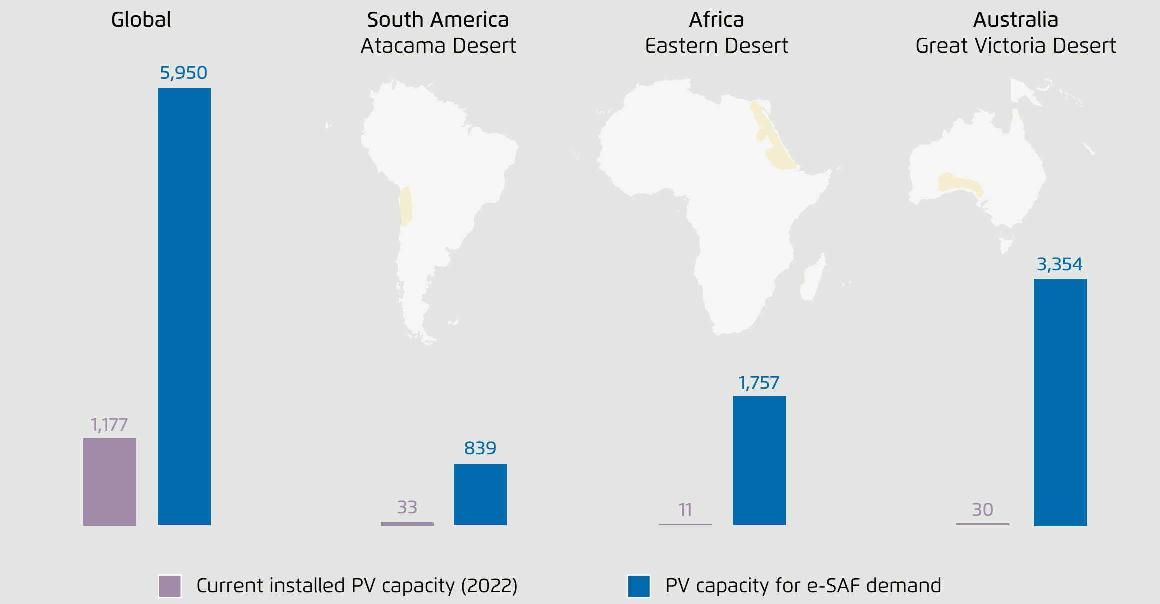
there are numerous desert regions that offer highly attractive conditions for renewables production, not least because they are sparsely populated. Across Africa, Australia and South America, various deserts, including the Eastern Desert, Great Victoria Desert and Atacama Desert, have the potential to produce vast quantities of renewable electricity. Theoretically, overall G20 fuel demand could be met with renewables capacity in these three regions. Figure 22 shows the resulting PV capacity that would need to be additionally installed in these regions in relation to their land area as well as, each region's currently installed capacity. As the figure makes evident, the roughly 5.9 terrawatts needed cover e-SAF production alone exceeds current capacities by many multiples. While globally installed PV capacity has significantly increased over the last decade in a trend that is most likely continue, the installation of additional PV capacity that would be needed to produce sufficient e-SAF requires a globally joint effort.

These estimates show that the mission to defossilise aviation is extremely challenging and will most likely not be achieved by e-SAF alone – at least within the coming decades, even given a focus on import from sweet spot regions. To master this challenge, all sustainably scalable and viable options at hand will need to be exploited and developed. In coming years, bio-SAF produced from waste oils and fats via the HEFA process represents the most promising option from an economical perspective. This can be supplemented with bio-alcohols from AtJ processes. However, as the sustainable biogenic resources are limited, the parallel ramp-up of e-SAF production is imperative.

In light of the fact that highly favourable locations for renewables production are relatively rare from a global perspective, they should be harnessed in a judicious and sustainable manner. As additional sectors of the economy electrify as part of the broader energy transition, demand for renewable electricity will further increase. At

Required PV capacity to fully substitute the worldwide jet fuel demand by e-SAF — Figure 22

In GW, compared to current PV capacity, globally and split up among continents with typical sweet spot regions (indicated here by selected deserts), share in required capacity proportionate to share in global land area



Agora Verkehrswende and International PtX Hub (2024) | Note: Authors' projection, data in appendix. Source: Installed PV capacity from IRENA (2023).

the same time, in many regions with favourable production conditions for e-SAF, renewable energy remains underdeveloped, and in some cases, local populations do not have access to any form of electricity.

While this section has focused exclusively on estimating electricity demand so far, associated hydrogen production would also require large quantities of purified water. Particularly in sunny regions, this will require significant seawater desalination capacities, which would further increase land requirements, power demand, and the stress placed on natural resources. A related issue is the need to consider the rights and interests of local communities in sparsely populated areas.

An additional and no less significant challenge pertains to the supply of sustainable carbon dioxide. As sustainable point sources are scarce, gigantic DAC facilities will be needed. To replace global jet fuel demand of 370 million t per year with e-SAF, roughly 1,925 million tonnes CO_2 will be required every year. If supplied by DAC, more than 50,000 of the biggest DAC plants currently in operation will be needed, covering an additional area of more than 190 square kilometers. However, these additional land use requirements are minor when compared to the land area that must be devoted to renewable generation. An additional factor is that the actual cost of direct air capture may be higher than anticipated in the past (some previous studies have predicted DAC costs of less than €100 per tonne of carbon dioxide by mid-century).[102]

And while biogenic CO_2 is another suitable source for carbon neutral e-fuels, it is normally supplied in a decentralized manner – when available at all – which would in term necessitate considerable logistical expenditures. In this way, sweet spot regions for renewable electricity are far from a panacea for mastering the challenges attendant to large-scale e-fuels production. One thing is clear: addressing these challenges will require an overarching strategy that considers all major dimensions of e-fuels production, including renewable electricity supply, sustainable carbon sources, and associated financing solutions.

102 Sievert et al. (2024).

9 | Conclusion

E-SAF is sure to play an essential role in the coming years as a replacement for fossil jet fuels in aviation, thereby reducing the climate impact of this sector. At the same time, e-SAF will likely remain expensive and only available in very limited quantities for decades to come. Accordingly, concerted efforts should be made toscale up global e-SAF production and tap economies of scale. However, other hard-to-abate sectors such as shipping and parts of the chemical industry will also rely on e-fuels, thus entering into demand competition with the aviation sector..

Given the tremendous global potential for renewables generation, achieving high e-SAF production figures would appear easily achievable at first glance. However, an ambitious production ramp-up is necessary to reduce costs and enable large-scale deployment. Indeed, major investment volumes are required not only to develop of e-fuel production facilities, but also expand renewable generation and achieve technical advancements in the area of direct air capture (DAC). From the outset, a clear focus should be placed on producing SAF for air and sea transport, as e-fuels are the only long-term climate protection option for abating residual energy demand in these subsectors. In this way, production facilities should align their product range with the needs of aviation and maritime shipping. Secondary products (such as e-naphtha) inherent to the production process can then be used to defossilise other modes of tranport in the run up to a fully electrified transport sector. In addition, these secondary products can be used to defossilise the subsectors of chemicals industry that continue to rely on carbon-based raw materials.

In view of the small amount of currently planned production capacities and the fact that in most markets regulatory frameworks are still being deliberated, the global production volumes anticipated up to 2030 are very low, even given an ambitious ramp-up. Accordingly, the e-fuel quantities that can be produced in the coming years must be reserved for use by hard-to-abate sectors, such as aviation. Indeed, from an environmental and economic policy perspective, it will only be sensible for the existing road vehicle fleet to begin relying on e-fuels insofar as sufficient quantities of e-fuels are already being produced to fully serve the needs of hard-to-abate sectors. And even under very optimistic assumptions, this will not occur before 2035.

When developing e-SAF production sites around the globe, the interests of all concerned countries and regions will need to be taken into account in an equitable manner. In particular, sufficient quantities of renewable energy must be reserved for domestic consumption in countries that are to serve as e-SAF exporters. Furthermore, efforts should be made to support domestic value creation in countries that are to receive foreign direct investment in e-SAF production infrastructure. Therefore, linkages to existing economic structures should be strengthened or newly established. If a global e-SAF economy were to exploit and perpetuate existing unequal power relations – as exists, for example, in the oil trade – this could lead to undesirable developments, including geopolitical tensions on the macro level or the marginalization of vulnerable groups on the micro level.

As discussed in this paper, policy measures that seek to encourage the development and use e-SAF are being introduced in an increasing number of countries. These measures (including blending quotas, subsidy mechanisms, and sustainability criteria) should be further strengthened and expanded. However, one main takeaway from our analysis is that comprehensive regulatory frameworks for the sustainable production and use of e-SAF are for the most part still at an early stage of development, and in some cases there is a sole focus on hydrogen. Overall, the risk of market fragmenation and carbon leakage will decline as the number of countries introducing comprehensive policy measures increases. At the same time, countries are subject to widely divergent political and economic conditions which must be taken into account when devising measures to support and regulate the market ramp-up of e-SAF. All relevant actors – including national governments, companies, and international organizations – should thus focus on encouraging the rapid expansion of e-SAF production while also striving to reducing production costs. In this connection, targeted R&D measures should be undertaken to further optimize e-fuel production processes and make sustainable sources of CO_2 available, particularly through direct air capture.

Realizing a climate neutral transport sector in line with the targets of the Paris Agreement is an enormous challenge, especially in hard to abate sectors such as aviation. To be sure, e-SAF will play a crucial role in defossilising the aviation sector. Yet encouraging energy efficiency will remain important, to keep e-SAF production quantities as low as possible. In addition to technology-based efficiency improvements, important demand-reduction measures include encouraging a modal shift and reliance on direct electrification or hydrogen whenever possible. Nevertheless, given the enormous demand for e-SAF that will result as part of the shift to climate neutrality, a sole focus on developing production capacities in sweet spot regions will not be sufficient. Indeed, a new overarching strategy for the supply of carbon-neutral e-SAF is necessary, one that addresses all major facets of their production, including renewable energy supply, sustainable carbon inputs, and associated financing needs, yet without losing sight of the imperative to support inclusive economic development and a just transition.

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List of abbreviations

AEL	Alkaline Electrolysis
ATJ	Alcohol-to-Jet
Avgas	Aviation gasoline
BtL	Biomass-to-Liquids
CapEx	Capital Expenditures
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CB	Certification Bodies
CtL	Coal-to-Liquids
CH	Catalytic Hydrothermolysis
COP	Conference of the Parties
CPA	Carbon Purchase Agreement
DAC	Direct Air Capture
DFI	Development Finance Institutions
EEA	European Economic Area
EESG	Environmental, Economic, Social, and Governance
EU ETS	European Union Emission Trading System
FC	Fuel Cell
FinEx	Financial Expenditures
FPIC	Free, Prior, and Informed Consent
FTS	Fischer-Tropsch Synthesis
FT-SPK	Fischer–Tropsch Synthetic Paraffinic Kerosene
GtL	Gas-to-Liquids
GHG	Greenhouse Gas Emissions
HC	Hydrocarbons
HEFA	Hydroprocessed Esters and Fatty Acids
HFS	Hydroprocessed Fermented Sugars
HPA	Hydrogen Purchase Agreement
IRA	Inflation Reduction Act
LC	Lignocellulose
LCA	Life-Cycle Analysis
LH2	Liquid Hydrogen
MDB	Multilateral Development Banks
MtG	Methanol-to-Gasoline
MtJ	Methanol-to-Jet
MtX	Methanol-to-X
OpEx	Operational Expenditures
PEMEL	Polymer Electrolyte Membrane Electrolysis
PoS	Proof of Sustainability
PPA	Power Purchase Agreement
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaic
RCF	Recycled Carbon Fuel
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
RTFO	Renewable Transport Fuel Obligation
RWGS	Reverse Water Gas Shift

SOEL	Solid Oxide Electrolysis
SAF	Sustainable Aviation Fuels
SBC	Synthetic Blending Component
SDG	Sustainable Development Goals
SIP	Synthetic Isoparaffins
SK	Synthesized Kerosene
SKA	Synthesized Kerosene with Aromatics
SPK	Synthetic Paraffinic Kerosene
UNGP	United Nations Guiding Principles on Business and Human Rights
UCO	Used Cooking Oil
VS	Voluntary Scheme
WEC	Wind Energy Converter
WPA	Water Purchase Agreement
WtL	Waste-to-Liquids

Annex

List of announced projects for e-fuels production via the Fischer-Tropsch route (not exhaustive)

Table 6a

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
–	Channel Infrastructure, Fortescue Future Industries	48,000 (n.s.)	Planned	Fortescue (2023a)
–	Ineratec	3,500 (2024)	Under construction	Ineratec (2022)
	Ineratec, Zenith Terminals	35,000 (2027)	Planned	Ineratec (2023)
–	Infinium, Mo Industrial Park	Not specified	Planned	Infinium (2024a)
–	P2X-Europe, The Navigator Company	40,000 (2026)	Planned	The Navigator Company (2022)
Alpha Plant	Climeworks, Lux-Airport, Norsk E-Fuel, Paul Worth SMS Group, Sunfire, Valinor	40,000 (2026)	Planned	Norsk E-Fuel (2024)
Bilbao Decarbonization Hub	Enagas, Repsol, EVE	2,100 (2024)	Planned	argusmedia.com (2022)
Brazoria electrofuels	Denbury, Infinium	Not specified	Planned	Infinium (2022)
Breogán Project	Greenalia, P2X Europe	20,000 (2027)	Planned	P2X Europe (2024)
Carbonshift PtL	Willis Sustainable Fuels	14,000 (2026)	Planned	WLFC (2023)
Concrete Chemicals	Cemex, Enertrag, Sasol	7,600[d] (2027) 30,500[d] (2030)	Planned	Concrete Chemicals (2023)
e-Alto	Clariant Catalysts, Technip Energies, Velocys	Not specified	Planned	Velocys (2022)
E-Fuel 1	Nordic Electrofuel, P2X-Europe	8,000 (2026)	Planned	P2X Europe (2023)
Fairfuel	Atmosfair	350 (2022)	In operation	Atmosfair (2023)
Green Fuels Hamburg	Airbus, Uniper, Siemens Energy	10,000[d] (2026)	Planned	Green Fuels Hamburg (2023)
HyShiFT	Enertrag, Hydregen, Linde, Sasol	Not specified	Planned	HyShift (2023)
IðunnH2	IðunnH2	45,000[d] (2028)	Planned	IðunnH2 (2024)
KerEAUzen	Air France-KLM, Engie	70,000 (2028)	Planned	Engie (2023a)
Moses Lake E-Jet Plant	Twelve	121[d] (2024)	Under construction	FastCompany (2023)
NetZeroLEJ	Airbus, DHL, HH2E, Sasol	200,000 (n.s.)	Planned	HH2E (2023)
NextGate	H&R Group, Mabanaft, P2X Europe	350 (2022)	In operation	P2X Europe (2022)
Pathfinder	Amazon, Howard Energy Partners, Infinium, NextEra Energy	Not specified	In operation	Infinium (2024b)
Plant Zero.1	Global E&C, Zero	Not specified	Under construction	Zero (2023)
Reuze	Engie, Infinium	100,000 (2026)	Planned	Reuze (2023)

List of announced projects for e-fuels production via the Fischer-Tropsch route (not exhaustive) Table 6b

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
SynKero	City of Amsterdam, KLM, Port of Amsterdam, Royal Schiphol Group, SkyNRG, SynKero	50,000[d] (n.s.)	Planned	Synkero (2023)
Vordingborg eFuels plant	Arcadia eFuels, Sasol, Topsoe	80,000 (2026)	Planned	Arcadia eFuels (2022)
Zenid One	Climeworks, SkyNRG, Uniper, Zenid	Not specified	Planned	Zenid (2023)

a In alphabetical order; listed companies were named in public communications in connection with the projects, this does not imply any financial involvement in the project.
b Total planned capacity in each case as announced; year refers to announced commissioning or expansion.
c According to public announcements as of March 2024; "Planned" includes all project phases from feasibility studies to concrete engineering.
d Data refers to e-kerosene only.

Agora Verkehrswende (2024)

List of announced projects for e-fuels production via the methanol route (not exhaustive) — Table 7a

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
–	AP Moller Holding, C2X, Maersk	300,000 (2028)	Planned	Hydrogen Insight (2023a)
–	AP Moller Holding, C2X, Maersk	1,000,000 (n.s.)	Planned	C2X (2023)
–	eFuel Steyerberg GmbH	52,500[d] (2026)	Planned	Spiegel (2023)
–	ReNew E-fuels Private Limited	500,000 (n.s.)	Planned	Hydrogen Insight (2023b)
–	ReNew E-fuels Private Limited	300,000 (n.s.)	Planned	Hydrogen Insight (2023b)
–	State Power Investment Corp	10,000[e] (2025) 400,000 (2030) 400,000[e] (2030)	Planned	Hydrogen Insight (2023c)
Aabenraa / Kassø	European Energy, Mitsu	42,000 (2024)	Under construction	European Energy (2023)
Antofagasta Mining Energy Renewable (AMER)	Air Liquide	60,000 (2025)	Planned	Enlit (2022)
eM-Rhône	Elyse Energy, GIE Osiris	150,000 (2028)	Planned	Elyse Energy (2023)
Finfjord e-meth-anol plant	Carbon Recycling International, Finnfjord, Statkraftl	100,000 (n.s.)	Planned	Carbon Recycling International (2023a)
FlagshipONE	Liquid Wind AB, Orsted	50,000 (2025)	Under construction	Ørsted (2023a)
FlagshipTWO	Liquid Wind AB, Sundsvall Energi	100,000 (2026)	Planned	Liquid Wind (2023)
FlagshipTHREE	Liquid Wind AB, Umeå Energi	100,000 (2027)	Planned	Liquid Wind (2023)
George Olah	Carbon Recycling International	4,000 (2012)	In operation	Carbon Recycling International (2023b)
Green Fuels for Denmark Phase 2a/2b	Everfuel, Haldor Topsøe, Nel, Orsted	50,000 (2025) 100,000 (2027)	Planned	Ørsted (2022)
Green Meiga	Clientes, Iberdrola	100,000 (2027)	Planned	European Commission (2023b)
Green UMI	Foresa, Iberdrola	2,900 (2025)	Planned	Iberdrola (2022)
Haru Oni	Empresas Gasco, ENAP, enel, ExxonMobil, HIF, Porsche, Siemens Energy	350 (2022) 100[d] (2022)	In operation	HIF (2022)
HIF Cabo Negro eFuels facility	HIF	173,000 (n.s.) 70,000[d] (n.s.)	Planned	HIF (2023a) HIF (2024a)
HIF Matagorda eFuels facility	Bechtel Energy, Siemens Energy, Topsoe	1,400,000 (2027) 562,500[d] (2027) 475,700[e] (2030)	Planned	Cision PR Newswire (2022b) Biofuels Central (2023b
HIF Paysandu	HIF	700,000 (n.s.) 250,000[d] (n.s.)	Planned	HIF (2023b)
HIF Tasmania eFuel facility	HIF, Technip Energies	210,000 (2028) 56,250[d] (2028)	Planned	HIF (2024b)
Humansdorp	Earth and Wire, Enertrag, 24 Solutions	120,000 (2027)	Planned	Earth & Wire (2021)

List of announced projects for e-fuels production via the methanol route (not exhaustive) — Table 7b

Project	Involved parties[a]	Announced capacity (t/a)[b]	Status[c]	Sources
HyGATE Demonstrator	Mabanaft, Vast	7,500 (2027)	Planned	Mabanaft (2024)
IRIS	Motor Oil Hellas	Not specified	Planned	European Commission (2023b)
Jangada	energy4future, Hy2gen	64,000 (2028)	Planned	Hy2gen (2023a)
KeroSyn100	Raffinerie Heide, CAC	Not specified	Planned	KEROSyN100 (2023)
Madoqua Synfuels	Madoqua Ventures	Not specified	Planned	Madoqua Ventures (2023)
Masdar Hassan Allam Utilities E-Methanol	Hassan Allam Utilities, Masdar	100,000 (2026)	Planned	Reuters (2022)
Nascar	Cetaer, Técnicas Reunidas	37,000 (2026)	Planned	Offshore Energy (2023a)
Nautilus	EWE Netz, Hy2gen, revis bioenergy,	60,000 (2027)	Planned	Hy2gen (2023b)
Pacífico Mexinol	International Finance Corporation, Transition Industries	400,000 (2030)	Planned	Mexico Business News (2023)
Power-to-Methanol Lappeenranta project	Aker Carbon Capture, St1, SWECO	25,000 (2026)	Planned	Sweco (2023)
Power-to-X project in the Gulf Coast	Maersk, Ørsted	300,000 (2025)	Planned	Ørsted (2023b)
RHYME Bavaria	Wacker	15,000 (2025)	Suspended	Wacker (2024)
SolWinHy	Green Enesys, Viridi RE, SolWinHy Cádiz	29,000 (n.s.)	Planned	Businesswire (2023)
Tambor Green Hydrogen Hub	Enertrag, SEG Ingeniería	Not specified	Planned	Fuel Cell Works (2022)
Triskelion	Forestal del Atlántico	40,000 (n.s.)	Planned	European Commission (2023b)
Vanadis Fuels Project	Aliceco Energy, TEH2, Total Eren	400,000 (2029)	Planned	Renewables Now (2023)

a In alphabetical order; listed companies were named in public communications in connection with the projects, this does not imply any financial involvement in the project.
b Total planned capacity in each case as announced; year refers to announced commissioning or expansion.
c According to public announcements as of March 2024; "Planned" includes all project phases from feasibility studies to concrete engineering.
d Share of e-gasoline.
e Share of e-kerosene.

Agora Verkehrswende (2024)

Assumptions for calculating the land and energy requirements for the production of e-kerosene via the Fischer-Tropsch route, e-methanol and e-gasoline via the methanol-to-gasoline route (reference year 2030 if corresponding data is available) — Table 8

Process step	Parameter	Unit	Value	Source
Fischer-Tropsch Synthesis	H2 demand	kg_H2/kg_e-kerosene	0.74	DLR; TUHH; JBV (2021)
	CO_2 demand	kg_CO_2/kg_e-kerosene	5.20	DLR; TUHH; JBV (2021)
	Electricity demand	kWh_el/kg_FT products	0.035	DECHEMA (2021)
	Naphtha co-production	kg_naphtha/kg_kerosene	0.17	DLR; TUHH; JBV (2021)
	Diesel co-production	kg_diesel/kg_kerosene	0.49	DLR; TUHH; JBV (2021)
Methanol synthesis	H2 demand	kg_H2/kg_e-methanol	0.20	Lonis et al. (2021)
	CO_2 demand	kg_CO_2/kg_e-methanol	1.42	Lonis et al. (2021)
	Electricity demand	kWh_el/kg_e-methanol	0.252	Lonis et al. (2021)
Methanol-to-Gasoline process	H2 demand	kg_H2/kg_e-gasoline	2.87	Schemme, et al. (2020)
	CO_2 demand	kg_CO_2/kg_e-gasoline	0.40	Schemme, et al. (2020)
	Electricity demand	kWh_el/kg_e-gasoline	0.214	Jones; Zhu, (2009)
Electrolysis	Electricity demand	kWh_el/kg_H2	48.3	IEA (2022)
	Water demand	kg_water/kg_H2	10.11	Kuckshinrichs et al. (2017)
DAC	Electricity demand	kWh_el/t_CO_2	225	Fasihi et. al (2019)
	Land demand	m^2/(t_CO_2 a)	0.1	Viebahn et al. (2019)
PV systems (single axis, ø Europe)	Full load hours	h/a	1260	Renewables Ninja (2022a)
	Area specific yield	MW/km^2	108	Bolinger; Bolinger (2022)
PV systems (single axis, sweet spot)	Full load hours	h/a	2,287	Renewables Ninja (2022a)
	Area specific yield	MW/km^2	43.2	Bolinger; Bolinger (2022)
Onshore WEC (ø Europe)	Full load hours	h/a	2,086	Renewables Ninja (2022b)
	Area specific yield[a]	MW/km^2	840	Bogdanov; Breyer (2016)
Onshore WEC (sweet spot)	Full load hours	h/a	5,137	Renewables Ninja (2022b)
	Area specific yield[a]	MW/km^2	840	Bogdanov; Breyer (2016)
	Area specific yield[b]	MW/km^2	8.4	Bogdanov; Breyer (2016)
Offshore WEA (German North Sea)	Full load hours	h/a	3,606	Renewables Ninja (2022b)

a Net area requirement for wind turbine, foundation and access road considered.
b Gross area requirement for wind turbine, also takes into account the distance between the turbines to avoid shading effects.

Agora Verkehrswende (2024)

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Agora Verkehrswende is a Berlin-based think tank that seeks to promote climate-friendly mobility. Non-partisan and non-profit, it works together with key stakeholders in the fields of politics, business, academia and civil society to decarbonise the transport system. To this end, the think-tank team develops evidence-based policy strategies and recommendations.

The Advancing Transport Climate Strategies (TraCS), funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection's International Climate Initiative supports developing countries in assessing transport GHG emissions, in analysing emission reduction potentials and in optimising the sector's contribution to the mitigation target in countries' NDC.

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