Sustainable aviation fuels: success factors for the defossilization of aviation

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Preface

Aviation on the verge of a paradigm shift: sustainable aviation fuels as the basis for a more sustainable future

This study focuses on Sustainable Aviation Fuels (SAF) – one of the most exciting and forward-looking topics in modern aviation, jointly prepared by EY and the Fraunhofer Institutes IGB and UMSICHT. At a time when climate change and the need to reduce greenhouse gas emissions are becoming increasingly urgent, this study offers an insight into the opportunities and challenges associated with introducing SAF.

The aviation industry is facing a paradigm shift. With the introduction of SAF, we can significantly reduce our environmental impact and lay the foundation for a more sustainable future. This study illuminates the technical and regulatory framework conditions necessary to successfully implement SAF. It also provides a comprehensive overview of the different types of SAF, their production methods and the potential markets.

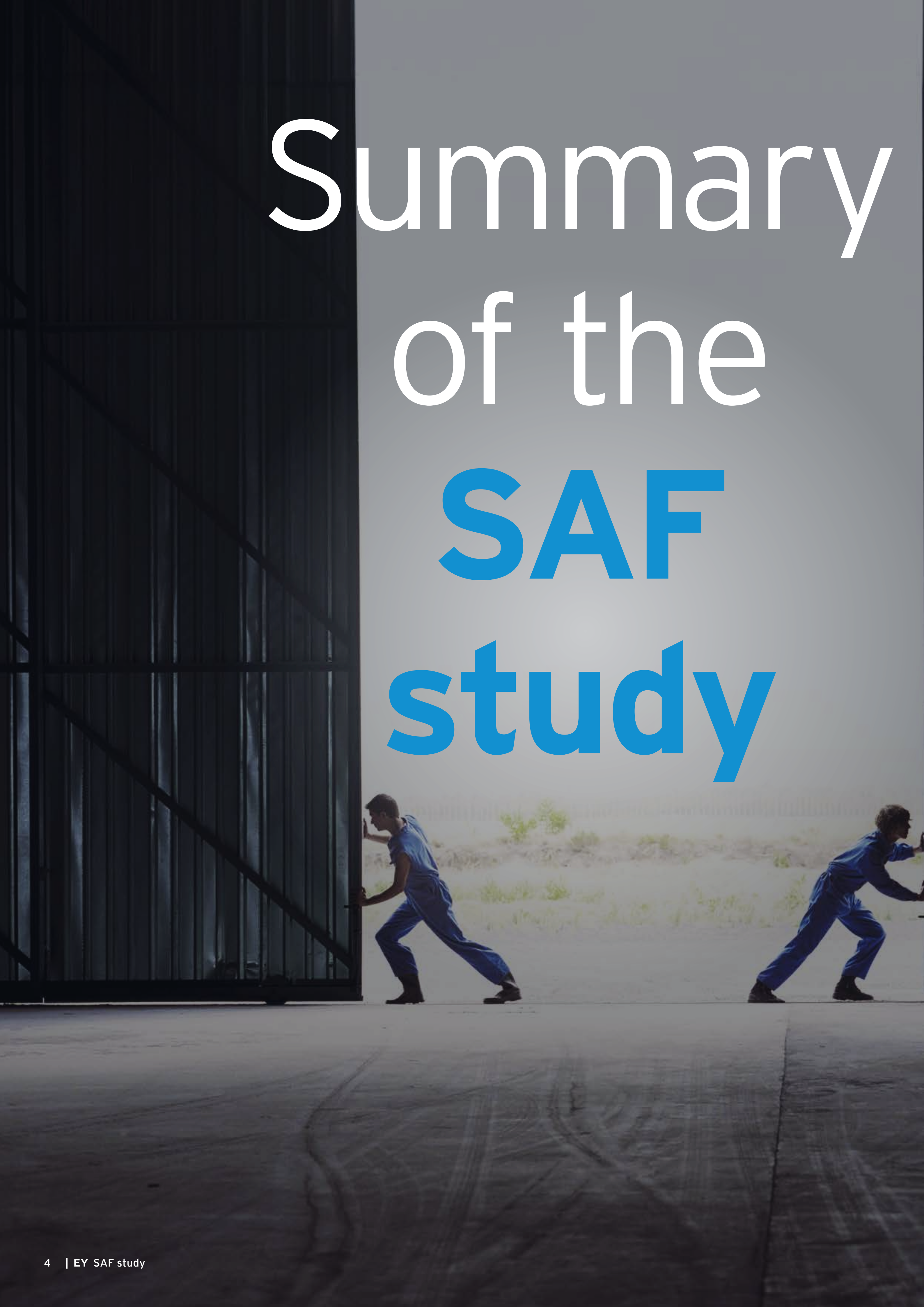
The study pays particular attention to current political discussions and regulatory developments intended to promote the use of SAF. The European Union has set ambitious targets to reduce emissions in the aviation sector with initiatives such as the 'Fit for 55' package and the ReFuelEU Aviation Regulation. These measures are crucial to driving the defossilization of aviation and achieving climate goals.

We have interviewed industry experts and conducted extensive research to give you a comprehensive picture of the current situation and future developments.

We hope that this study will not only arouse your interest but also serve as a valuable resource for your work. Immerse yourself in the world of SAF and discover the possibilities this innovative technology holds for the future of aviation.

We hope you enjoy reading it!

Summary of the SAF study



At the European level, the European Union (EU) adopted the “Fit for 55” package as part of the EU Green Deal. The regulations are intended to reduce greenhouse gas emissions in the EU by at least 55% by 2030 compared with 1990 levels. The EU has set itself the goal of achieving climate neutrality by 2050.[1]

How can the aviation industry’s net-zero objectives be achieved?

The aviation sector is currently focusing on three complementary strategies to reduce air traffic emissions: operational improvements, technological innovations and environmentally friendly fuel. The EU has issued new regulations to coordinate implementation. Stricter regulations under the European Emissions Trading System (ETS) will cause the price per tonne of carbon dioxide (CO) emitted to rise further and faster than previously planned. Secondly, the ReFuelEU regulations prescribe the increasing use of SAFs in aviation. SAF is renewable or sustainable aviation fuel that can be blended with conventional kerosene as a drop-in solution. Prescribed quotas are intended to encourage the aviation sector to use more SAF at airports between 2025 and 2050 and thus reduce emissions.

In 2021, the International Air Transport Association (IATA), representing around 348 airlines worldwide and over 80% of global air traffic, announced the objective of flying with net-zero emissions by 2050, bringing aviation in line with the goal of the Paris Climate Agreement. IATA predicts that SAF can contribute 65% of the air sector’s emissions reduction and thus significantly contribute to achieving the net-zero objective.[2]

This SAF study was created to gain a precise understanding of the market and technology development of SAF, to forecast demand and to identify relevant hurdles for the implementation of projects. Here are the most important contents per chapter:

1 | Technical framework conditions and SAF types

A distinction is made between organic and E-SAF, which differ in terms of raw material utilization and production routes. Globally, eight process routes are approved to produce SAF in accordance with the two certifications ASTM D1655 and ASTM D7566. ASTM D7566 regulates the procedures and the blending ratio, which is currently a maximum of 50%, while ASTM D1655 defines specifications for conventional and ASTM D7566 blended aviation fuels. Furthermore, ASTM D1655 also regulates the joint processing of biomass with crude oil, mostly referred to as "co-processing."

Bio-based SAF is produced from biomass and biogenic residues. These include plant and animal fats, sugar and lignocellulose biomass, and other raw materials not based on food based feestocks, such as intermediate and cover crops. In this study, the main production routes for bio-based SAF are considered, including Hydrogenated Esters and Fatty Acids (HEFA), Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), Fischer-Tropsch Synthesis Synthetic Paraffinic Kerosene (FT- SPK), Direct Sugars to Hydrocarbons (DSHC), Catalytic Hydrothermolysis (CHJ) and Hydrocarbon Hydrogenated Esters and Fatty Acids (HC-HEFA).

The production of E-SAF (also known as PtL-SAF) requires the use of renewable ("green") electricity. The electrical energy is chemically stored in the target products, namely the fuels. This is usually done through water electrolysis. In contrast to Bio-SAF, which is produced from biogenic raw materials, E-SAF production is based on the direct technical conversion of carbon dioxide (CO). The study focuses on two E-SAF production processes: the Fischer-Tropsch route with Fischer-Tropsch synthesis (FTS) as the central conversion step and the methanol route, in which methanol is obtained by converting CO_2 as an important intermediate product. While the methanol route is still in the process of technical approval for use in aviation, the Fischer-Tropsch route has already been approved in accordance with the ASTM D7566 specification. In the future, both process routes will play an important role in providing the quantities of SAF required for climate-friendly aviation. In either case, for the production of E-SAF, CO_2 and water are required as primary raw materials. Therefore, the provision of CO_2 in sufficient quality and quantity must be carefully considered as a prerequisite for the sustainable and scalable production of E-SAF. In principle, both extraction from CO_2-rich industrial waste gas streams (so-called point sources) and direct capture from the air are possible for this purpose.

2 | Regulatory framework

The EU has the ambitious objective of a net-zero emissions balance by 2050. Numerous measures have been taken to achieve this, including the European Green Deal introduced in 2019. This comprehensive plan is aimed at a sustainable transformation of the EU and includes relevant measures for the aviation industry, such as the European climate law, the "Fit for 55" package and the European industrial strategy. The European Renewable Energy Directive (RED III), the European Energy Emissions Trading System (EU ETS) and the ReFuelEU Aviation initiative were created as part of the "Fit for 55" program.

The ReFuelEU Aviation Initiative, which came into force at the beginning of 2025, marks a turning point in the aviation industry. It provides for the gradual introduction of SAF mandates, increasing from 2% in 2025 to 70% in 2050. This regulation not only counteracts common refueling practices that could lead to increased emissions but also penalties for violations.

From 2025, the European Aviation Security Agency (EASA) will introduce an environmental labeling system for aviation on behalf of the EU Commission and the EU Parliament, thus awarding eco-labels. It will provide passengers with transparent information about the environmental footprint of their flights, which should encourage them to choose sustainable flight options.

There are numerous initiatives and guidelines at the international level. One example of this is the Sustainable Aviation Fuel Certificate (SAFc) of the Clean Skies for Tomorrow (CST) initiative of the World Economic Forum (WEF). This voluntary framework is designed to facilitate the transition of global aviation to net-zero emissions.

Other international programs include the green premium, where customers pay the price difference between kerosene and the SAF price, as well as IATA's Emission Reduction Roadmap, which envisages a net-zero objective for the aviation industry by 2050. In addition, global emissions trading systems such as the UN aviation organization ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program have been introduced to ensure that CO_2 emissions from aviation do not rise above the 2020 level. This program will be voluntary until 2027 and mandatory thereafter, underlining the importance of emissions trading systems and their ability to create financial incentives to reduce emissions.

3 | Demand and customers

Global regulations and specific EU directives significantly influence the production and use of SAF, which in turn has a major impact on the market dynamics of supply and demand.

Interviews and in-depth research conducted as part of this study indicate an increasing demand for SAF in the coming years. By 2030, numerous airlines plan to cover 10% of their aircraft fuel requirements with SAF. According to our forecasts, an annual growth rate of 7% is expected from 2030 to 2050, leading to an increase from 49 million tonnes in 2030 to 196 million tonnes in 2050. In Europe, demand is forecast to increase by 11% annually between 2030 and 2050 – the highest of all regions.

To meet the demand for environmentally friendly fuel, airlines are increasingly entering long-term supply contracts with current and potential producers. In 2024, 20 such newly concluded contracts were announced worldwide. These not only ensure the availability of the product, but also continuous purchase. Although these agreements are often based on declarations of intent, they strengthen the safety of producers and underline the airlines' engagement for their sustainability goals. Currently, these collaborations focus almost exclusively on bio-based SAF, as contracts for E-SAF are limited by the pending commercialization and technological development.

The enormous projected demand for environmentally friendly fuel will require investments of US$1.0 trillion to US$1.5 trillion in production facilities by 2050. The airlines believe that the oil industry is primarily responsible for this. In addition, supply contracts should stimulate investment in future production facilities. There are also signs of increased cooperation between airports, airlines and companies to increase production capacities.

4 | Global production potential

According to current forecasts, SAF production will increase exponentially over the next few years. Between 2019 and 2022, the global production volume already increased significantly from 0.02 to 0.24 million tonnes of bio-based SAF. IATA assumes that SAF production will reach 2.1 million tonnes or 0.7% of total jet fuel production in 2025.

An internal analysis of planned and active SAF projects shows that North America leads the field with a forecast production potential of around 14 million tonnes per year by 2030, while production capacity in Africa remains comparatively low. Projects currently in the front-end engineering design (FEED) phase or under construction add up to a potential production volume of around 3.2 million tonnes per year by 2030. Not only is a general increase in global production volumes expected, but also a geographic expansion of production facilities. E-SAF will become increasingly important, especially in regions with limited biomass reserves. This could be due to the expected falling costs of H_2, electrolysis and DAC technologies. Even stronger growth is expected for bio-based SAF production.

Existing production gaps were identified in the APAC region and the Middle East in particular. Here, a possible deficit of 20.4 million tons per year is forecast by 2030, provided that SAF production capacities are used to maximum capacity. These findings underscore the urgency of increasing global SAF production capacity to meet increasing demand.

5 | Infrastructure and logistics

Scaling up the production and use of SAF requires substantial infrastructure investments across both the production and distribution value chains. Unlike conventional kerosene, SAF production infrastructure is highly specific to the chosen pathway. Bio-based SAF relies on dedicated systems for the collection, storage, and processing of biomass. In contrast, e-SAF production demands the development of electrolysis capacity, access to large volumes of renewable electricity, suitable site locations, and a reliable supply of CO_2. To comply with the 2% E-SAF regulation in Germany, 7.5 TWh of electricity from renewable sources and 1 million tonnes of CO_2 are needed. The volatile renewable energies require an innovative approach, such as using H_2 storage, to effectively utilize the electricity. To provide the necessary amounts of CO_2 in Germany, an additional 250 DAC plants need to be put into operation. Indirect CO_2 utilization through biomass is also conceivable.

The admixture or (virtual) use of SAF can be carried out according to three models: the segregation method, the mass balance method and the book-and-claim system. A major advantage of the latter method is that SAF can be refueled close to the production site and claimed elsewhere.

The existing distribution infrastructure can continue to be used due to the similarity between conventional kerosene and SAF blends. This includes the transportation of SAF from the production sites to the airports by truck, train, ship or pipeline. The use of pipelines is only permitted in certain countries and only for certified SAF. With the increase in SAF use, storage capacities must be expanded by building new fuel storage facilities. SAF blends can either be stored separately from conventional jet fuel or in the same tanks using mass balance, with the latter reducing the required infrastructure and thus saving costs.

Environmentally friendly fuels are currently still up to six times as expensive as conventional kerosene. According to EY calculations, the global minimum selling price in 2024 was US$2.7/kilogram (~US$2,680/tonne) for bio-based SAF and US$4.9/kilogram (~US$4,880/tonne) for E-SAF. This results in a current cost difference of approximately US$2.2/kilogram (~US$2,200 US/tonne) between bio-based SAF and e-SAF.

Over time, we predict that the minimum selling price for bio-based SAF will increase by approximately 19% globally to US$3.2/kilogram (~US$3,180/tonne), for example, due to potential shortages of raw materials, while the minimum selling price for E-SAF will decrease by approximately 54% globally to US$2.2/kilogram (~US$2,240/tonne), for example, due to technological advances. In 2050, the global price difference will, therefore, be around US$0.9/kilogram (~US$940 US/tonne).

The necessary infrastructure for SAF expansion will require investments of US$1.00 trillion to US$1.45 trillion by 2050. Due to the growing interest in SAF, private investment is increasing worldwide. Public funding is also playing a key role in the development of the market. There are already many government subsidy projects worldwide, particularly in Europe and North America, as well as in selected countries in the APAC region.

The efficient expansion of SAF projects requires sufficient bankability to secure solid financing. Key factors for this include economic profitability, reliable technologies, the availability of raw materials, government funding, subsidies and legal framework conditions, fixed purchase agreements, a focus on sustainability and the minimization of risks. In addition, the scalability of the projects should be ensured to maximize the SAF capacities. Chapter 6 focuses on the areas of technology, infrastructure, economics, regulation and sustainability, as these factors significantly influence scalability.

The expansion of SAF production and use poses environmental, social and regulatory challenges but also offers significant opportunities and potential for ESG sustainability. An in-depth understanding of these interactions is required to ensure effective and efficient management. For example, implementing a bio-based SAF project in Canada is expected to create 1,500 construction jobs and 150 full-time positions, with a planned plant capacity of 3.18 million liters (2,521.74 tonnes) per day. However, the transformation from conventional aviation fuel to SAF entails the risk of job losses in the fossil fuel sector.

8 | Recommendations for action

Based on the forecasts for demand and production in the coming decades and the status quo of SAF production, we have developed concrete recommendations for the successful scaling of SAF production. These recommendations focus on the increased provision of financial resources and the advancement of technological progress in Europe. We propose the establishment of a central fund at the EU level that receives money from various regulatory resources and invests it strategically in the development of the SAF industry. This fund could be managed by the European Hydrogen Bank (EHB). The proposed regulatory funds are fines resulting from non-compliance with the ReFuelEU regulation and revenues from the EU ETS. In addition, money from a capital market-oriented pension fund, such as the recently adopted generation capital in Germany, can be invested in SAF projects in return for interest payments. Furthermore, a mandatory levy on airline ticket purchases could be introduced along the lines of the compensation payments that are currently often offered voluntarily. Finally, a tax on income SAF production in the co-processing procedure would also be conceivable to finance the dedicated SAF fund. In addition to financial support, there are also technical improvements.

According to our forecast, the use of co-processing (the use of existing refineries for SAF production) will initially be a supplementary approach to ramp up SAF production and build up the SAF market. This technology will be necessary to make SAF production bankable and to enable the required SAF scaling.

In addition to CO_2 emissions, non-CO_2 effects such as nitrogen oxides, soot particles, oxidized sulfur compounds and water vapor also influence the climate in aviation. The contrails produced by aircraft in the sky can have either a cooling or warming effect, depending on the ambient conditions. Using SAF can reduce both CO_2 and non-CO_2 effects, as SAF releases fewer soot particles and other greenhouse gases. However, the complete elimination of non-CO_2 effects by SAF alone is not possible. Further measures, such as the optimization of flight routes or flight altitudes, are required.

Content

1

Production technology and SAF types

2

3

4

5

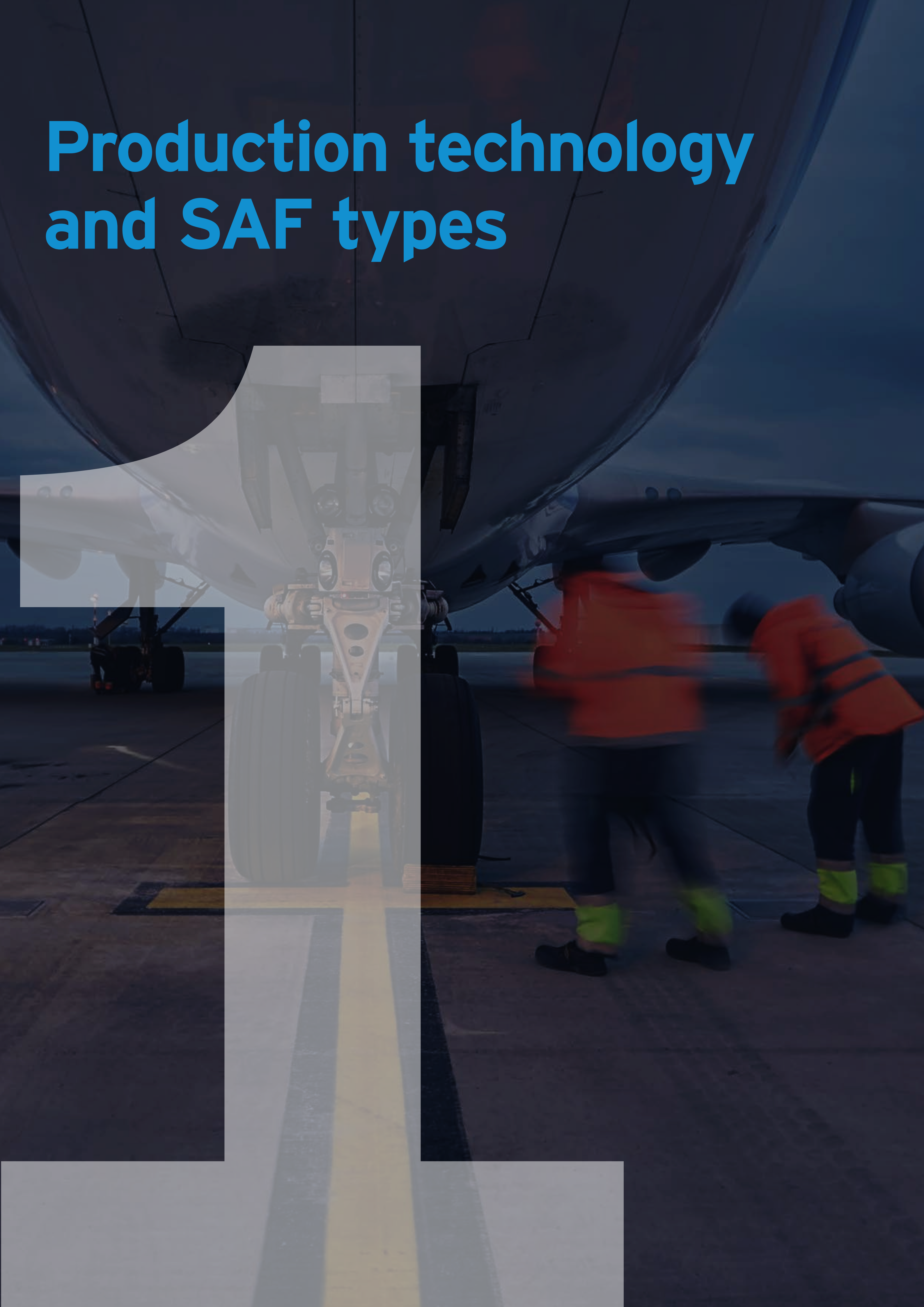
6

7

8

Production technology and SAF types

1



> In addition to HEFA, we see alcohol-to-jet as the most promising technology for SAF production in the coming years. Despite the very high feedstock potential of gasification-Fischer-Tropsch technology, we see hardly any progress in its application. In general, however, we have no preferences as long as the SAF is produced from sustainable feedstocks and its affordable and reliable production is ensured.

Henrik von Storch, Director Global Sustainable Aviation Fuels, DHL Express

Introduction and summary of the chapter

The following Chapter 1 summarizes the current processes in the production of sustainable aviation fuels (SAF) and the corresponding regulations and technical developments. In principle, a distinction can be made between the production of bio-based SAF and E-SAF, even if hybrid approaches are possible in which both biogenic and electricity-based raw materials are used. The term Power-to-Liquid-SAF (PtL-SAF for short) is also used in the literature for E-SAF. Chapter 1.1 describes in detail the various process routes that have already been approved for the production of SAF (plus the methanol route, which has not yet been approved).

These process routes differ mainly in the type of raw materials used to produce SAF. These, in turn, influence the specific work steps and the processes involved. It should also be noted that the production processes do not exclusively produce SAF. Other sustainable fuels, such as diesel and gasoline fractions (e.g., biodiesel), are also obtained as by-products in varying proportions. The type of by-product generated depends on the specific production pathway. In addition to the conventional process (route 0) for producing fossil kerosene from crude oil, eight alternative pathways for bio-based SAF are under consideration. In these routes, the aircraft fuel is produced from various sources, including fats, oils, alcohols and sugars. Additionally, the power-to-liquid (PtL) production of E-SAF is explained using two different chemical processes.

However, it is important to note that SAF may currently only be used as a blend with fossil aircraft fuel (Jet-A1). The blending rates differ depending on the process route and amounted to a maximum of 50% at the time this study was prepared. However, efforts are being made to obtain approvals for flights with 100% SAF in the future. Such use has already been successful in test flights.

Chapter 1.2 describes the approval of SAF in the context of the associated specifications and the current status. This technical evaluation and approval is carried out in the form of specifications defined by the American Society for Testing and Materials (ASTM). These standards regulate the production of SAF via the various process routes and the blending with fossil kerosene. In this way, the characteristics, suitability and required properties of SAF can ensured. This is essential to ensure safety in flight operations.

1.1 SAF types

1.1.1 Bio-based SAF from different biomasses

Bio-based SAF refers to SAF obtained from biomass and biogenic residues as initial material. The range of input materials is broad and extends from waste oil to agricultural residues. Accordingly, there are numerous different processes for producing Bio-SAF. The eight process routes described below are already covered in the associated standards. The process routes approved by ASTM are listed in Table 1 with their technical names and are briefly described below from raw material to refueling.

ASTM D7566 currently limits the amount of synthetic components to 50%. This means that, currently, the use of corresponding bio-based SAF is only possible as an admixture (blending) to conventional fossil aircraft fuel. The use of pure SAF without blending with fossil fuels is not yet possible due to quality testing, as its lower density can affect the range of aircraft. In addition, the slightly different chemical composition, in particular the changed proportion of aromatic compounds, causes seals in the tank and turbine system to shrink. The flat distillation curves, which have a different ratio of highly and low volatile fuel components, hurt combustion in the turbine. Therefore, blending conventional aviation fuel, also known as jet fuel (Jet-A1), is currently essential to ensure the required fuel quality for existing aircraft technology. However, a further development is progressing rapidly. For example, pure SAF has already been produced and used in commercial aircraft to replace 100% of fossil aircraft fuels without fossil fuels additions.[3,4,5] Despite minor current quality differences, SAF is designed as a "drop-in fuel", meaning that when blended according to certified process pathways, it is entirely equivalent to conventional Jet-A1 aviation fuel. Consequently, the storage and handling procedures for standardized blends of SAF and fossil Jet-A1 are identical and are considered "fully fungible".[b]

Table 1

Approved SAF types (ASTM D1655 and ASTM D7566)[a]

Route name, Standard, associated annex	Description and name abbreviation according to ASTM
Process route 1, ASTM D7566 (Annex 2)	■ Bio-based SAF from fats and oils (HEFA) ■ Synthesized Paraffinic Kerosenes (SPK) from hydroprocessed esters and fatty acids
Process route 2, ASTM D7566 (Annex 5)	■ Bio-based SAF from alcohols (ATJ-SPK) ■ Only isobutanol and ethanol are currently certified
Process route 3, ASTM D7566 (Annex 1)	■ Fischer-Tropsch-SPK (FT-SPK)
Process route 4, ASTM D7566 (Annex 3)	■ Bio-based SAF from sugars (DSHC/SIP)
Process route 5/6, ASTM D7566 (Annex 6 and 7)	■ Bio-based SAF from other raw materials (CHJ and HC-HEFA) ■ Catalytic Hydrothermolysis Jet Fuel (CHJ, Annex 6), Hydrocarbon-Hydroprocessed Esters and Fatty Acids (HC-HEFA)
Process route 7, ASTM D7566 (Annex 8)	■ Bio-based SAF with aromatics from alcohols (ATJ-SKA) ■ Mixtures of alcohol fractions from ethanol to pentanol can be processed simultaneously
Process route 8, ASTM D1655	■ Co-processing of bio- and Fischer-Tropsch intermediates with crude oil in the refinery (co- processing)

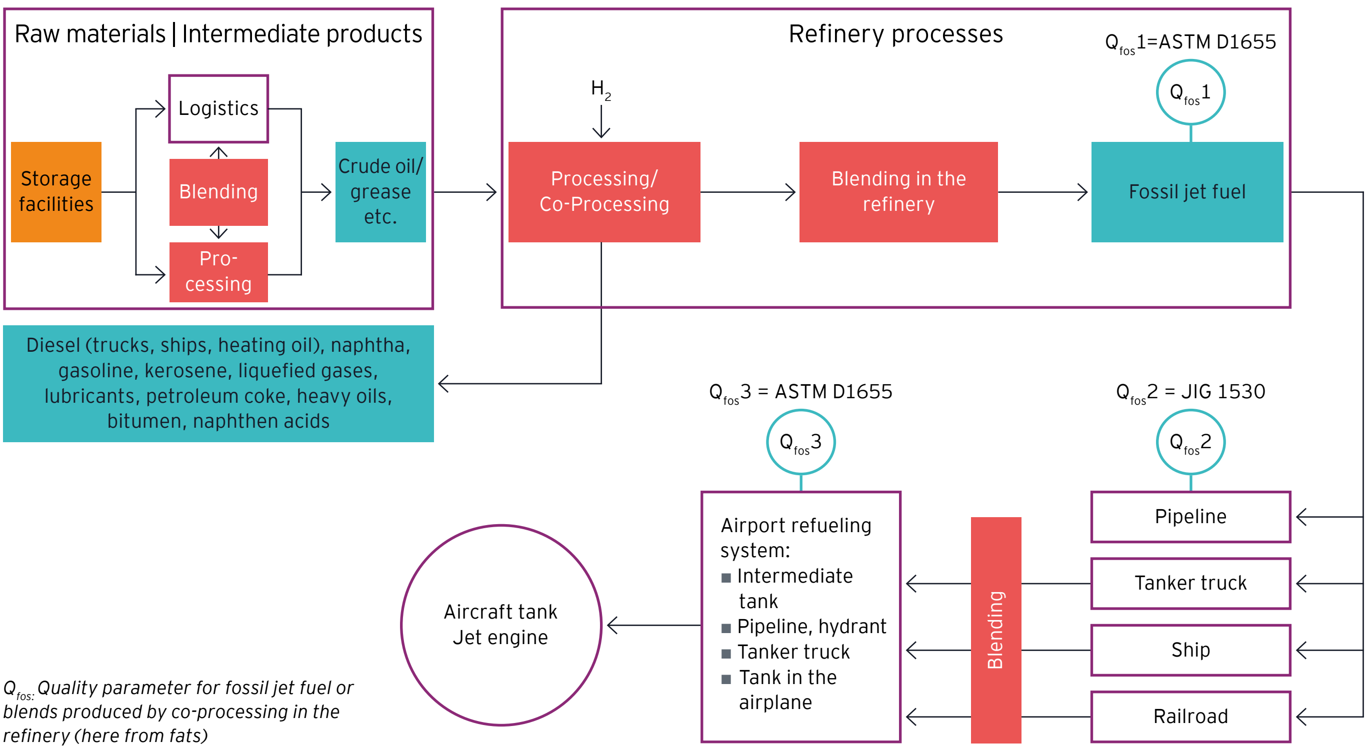
a Definition from ASTM D7566 for SPK: "synthesized paraffinic kerosine = synthetic blending component that is comprised essentially of iso kerosenes, normal kerosenes and cycloparaffins", SKA:= SPK plus aromatics

b Energy Institute and Joint Inspection Group: EI/JIG 1530 Standard Quality Assurance Requirements for the Manufacture, Storage & Distribution of Aviation Fuels to Airports (A4), May 2019

Process route 0: Aviation fuel from crude oil
As already mentioned, SAF is currently used exclusively for blending into fossil aircraft fuels (Jet-A1). Therefore, the conventional process route 0, which comprises the production of aviation fuel from crude oil, is described first (Figure 1). The presentation of the individual process steps is divided into the following areas:

Figure 1
Illustration of process route 0: aviation fuel from crude oil – optionally also with alternative raw materials for co-processing such as fats – with Qfos quality controls *(Source: Fraunhofer)*

1	**Sources of raw materials,** i.e. approved raw materials and crude oils, which are usually limited by refinery type, extracted products or intermediate products	● (orange)
2	**Products** or **Intermediate products**	● (teal)
3	**Conversion steps (chemical, physical, biological)**	● (red)
4	**Logistics,** i.e. storage, transportation and refueling at the airport	○



Q_{fos}: Quality parameter for fossil jet fuel or blends produced by co-processing in the refinery (here from fats)

Although little is published about the associated refinery processes, it is clear from the ASTM specifications how quality parameters must be maintained and monitored in the supply chain of conventional aviation fuel (Table 2).

The frequency of the product quality measurements, according to Table 2, depends on the technological maturity of the SAF process route and, therefore, varies, at least for the time being. Only one SAF at a time may be added via the blending process, i.e., the aforementioned process routes may not currently be combined by blending, and the mixtures are only considered identical to fossil Jet-A1 in this way.

For all the process routes described below (1 to 7), the raw materials and intermediate products, conversion steps and the structure of the production systems (decentralized versus centralized production structures) are very different in some cases.

Also, the exact number of generated certificates according to Table 2 varies and is reduced in terms of perspective in accordance with the current ASTM D7566. The control of quality parameters is only specified for the last step of the production of the respective SAF before blending with fossil Jet-A1 via the ASTM D7566 standard and for the co-process via ASTM D1655.

Table 2

Quality control points Q_{fos} for SAF

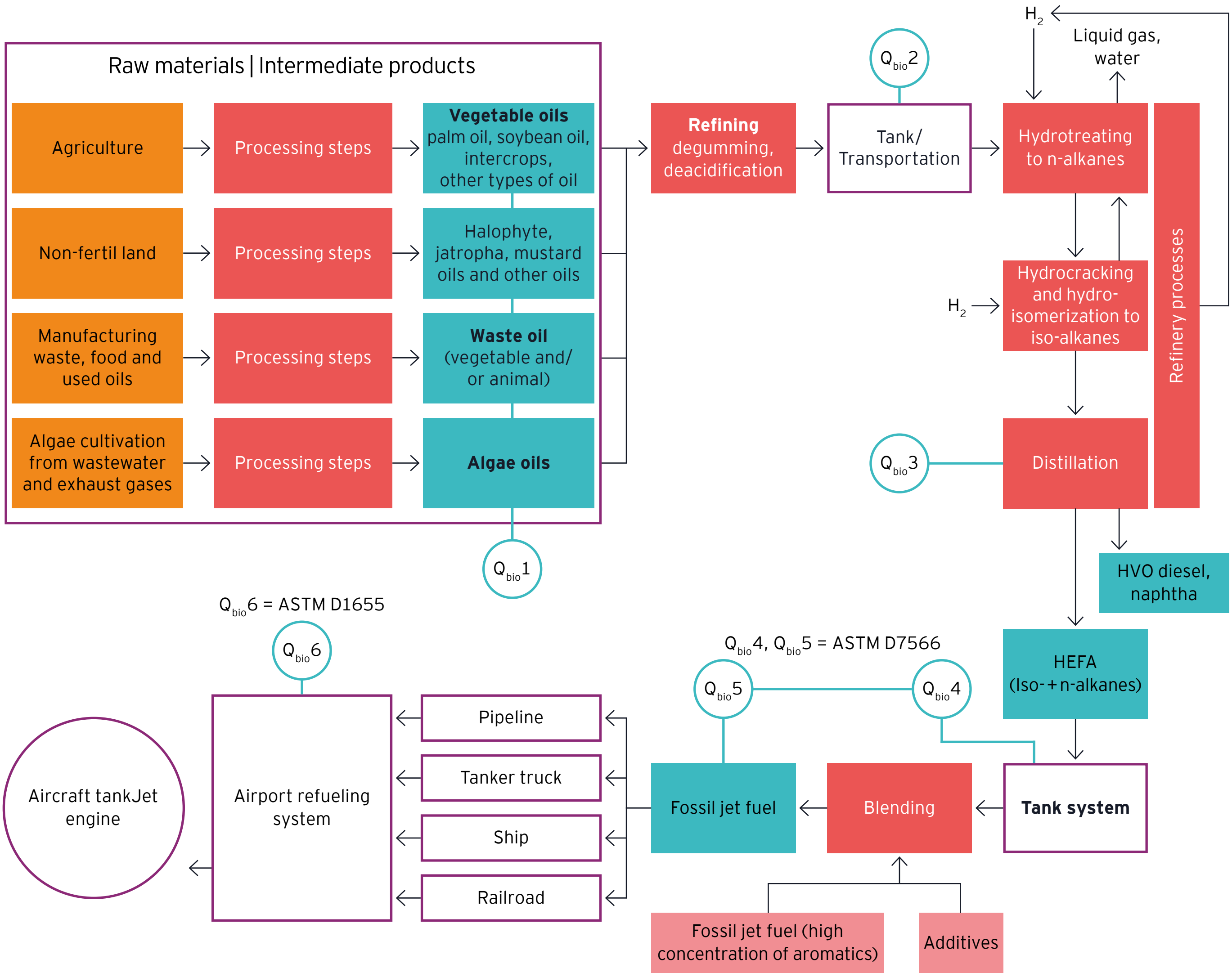
(Source: Energy Institute, Joint Inspection Group 2019[6])

Type	Parameters	Specification	Certificate EI/JIG1530/JIG1533
$Q_{fos}1$	Complete analysis	ASTM D1655	**RCQ – REFINERY CERTIFICATE OF QUALITY** Issued by the manufacturer's laboratory (or a laboratory working on behalf of the manufacturer). It contains information on the addition of additives, both their type and quantity. It also contains information on the identity of the refinery of origin and the traceability of the described product.
$Q_{fos}2$	Partial analysis	EI/JIG 1530 (Table 2)	**RTC – RECERTIFICATION TEST CERTIFICATE** Analysis of parameters that are particularly susceptible to contamination. This proves that a recertification test has been carried out to verify that the quality of the aviation fuel in question has not changed and remains within the specification limits, e.g., after transportation in sea tankers or in multi-product pipelines.
$Q_{fos}3$	Partial analysis	ASTM D1655 (Table 1)	**COA – CERTIFICATE OF ANALYSIS** Issued by a certified laboratory other than that of the refinery of origin. Does not provide information on additives or the percentage of hydroprocessed or synthetic components.

Quality

Process route 1: Bio-based SAF from fats and oils (HEFA)
In process route 1, vegetable oils such as soybean oil, camelina oil, jatropha oil, as well as recycled frying and animal fats and residues from vegetable oil processing are converted. The use of edible vegetable oil, for example, has now been largely restricted in many EU countries or is not counted towards blending quotas for biofuels. The use of algae oils, which contain plant-analogous oils, is possible, but the economic viability of this is limited. The first processing step involves pretreatment of the oils by degumming and deacidification, whereby catalyst toxins and free fatty acids (FFA) are separated. This is followed by several processing steps that consume H_2. Specifically, these are hydrotreating, i.e., hydrogenation to remove all non-carbon atoms, as well as hydrocracking and hydro-isomerization to adjust the carbon chain structure. This is followed by distillation to separate all fractions according to their boiling points. The products and by-products consist of straight n-alkanes and branched isoalkanes in the aviation fuel boiling range together with other chemically very similar valuable fractions. This essentially includes HVO diesel (hydrogenated vegetable oil, usually an expensive winter diesel grade) and naphtha, which is used as light petrol or as a raw material for plastics production.

Figure 2
HEFA process route
(Source: Fraunhofer)



Source
Product, Intermediate
Conversion
Logistics

Q_{bio}: Quality parameter for jet fuel based on fats and oils
HVO: hydrogenated vegetable oils (diesel); HEFA: hydroprocessed esters and fatty acids

The H_2 requirement for production plants designed for HVO diesel or for HEFA-SAF as the main product depends on the type of fats and oils used. The following Table 3 provides an overview of averaged H_2 requirements and the yield for a plant for the production of HEFA-SAF. Based on industry surveys for the H_2 requirements and product yields of a HEFA plant operated with waste oils based on used fats and oils (UCO = Used Cooking Oil), the following table was prepared.

The relative additional demand for other typical fats and oils was roughly calculated according to the four raw material groups listed in Figure 2 (agriculture, infertile soils, manufacturing waste and algae cultivation). Some oil plant varieties, such as camelina, can grow on both fertile and infertile soils. As expected, however, the yield of oils and biomass is different.[7] It is assumed that these are pre-cleaned raw materials, which are fed into the system from the point marked with "$Q_{bio}2$". It is also assumed that the product's selectivities per raw material do not change and that a higher heat production achieved by a higher H_2 consumption does not cause any problems in terms of system technology. It should be noted that the figures are mean values for the composition of the oils, which were determined from literature data.

Table 3

Input and output "HEFA system" in kilograms/tonnes of grease or oil type

(Source: Fraunhofer)

H_2 Input	HEFA Output	HVO	Naphtha*	Propane***	Other****	Oil types (raw material group)
						(vegetable oils from agriculture)
61.8 kg	621.8 kg	138.3 kg	85.6 kg	95.7 kg	120.4 kg	Soybean oil
62.5 kg	622.2 kg	138.4 kg	85.7 kg	95.8 kg	120.4 kg	Camelina oil*****
						(vegetable oils from infertile soils)
62.5 kg	622.2 kg	138.4 kg	85.7 kg	95.8 kg	120.4 kg	Camelina oil*****
54.8 kg	617.1 kg	137.3 kg	85.0 kg	95.0 kg	120.4 kg	Jatropha oil
55.5 kg	617.6 kg	137.4 kg	85.0 kg	95.1 kg	120.4 kg	Salicornia oil
						(Oils from residual materials)
44.0 kg	610.0 kg	135.7 kg	84.0 kg	93.9 kg	120.4 kg	Frying fats
44.0 kg	610.0 kg	135.7 kg	84.0 kg	93.9 kg	120.4 kg	(Animal fats*)
						(Oils from algae)
-	-	-	-	-	-	Algae oils**)

** UCO and animal fats with an average molecular weight of the fatty acids of 276 and 273 g/mol respectively*
*** requires at least as much H_2 as for camelina oil*
**** Propane is sold as liquefied gas and is therefore also referred to as such in Fig. 2*
***** "Other" includes CO, CO_2, H_2, light hydrocarbons and water vapor*
****** Camelina and other oil plants not mentioned here, such as carinata, can be grown on both fertile and infertile soil and are therefore listed twice*

On the one hand, this process route is based on sugar, mostly from the food sector (food) and less from non-food. On the other hand, synthesis gas from industrial waste gases, such as blast furnace gas from steel production, can also be fermentatively converted to alcohols in the analogous process route. The alcohols are further processed into n-alkanes and isoalkanes via a refinery process with H_2. For a long time, only biological fermentation on the basis of alcohol was possible.

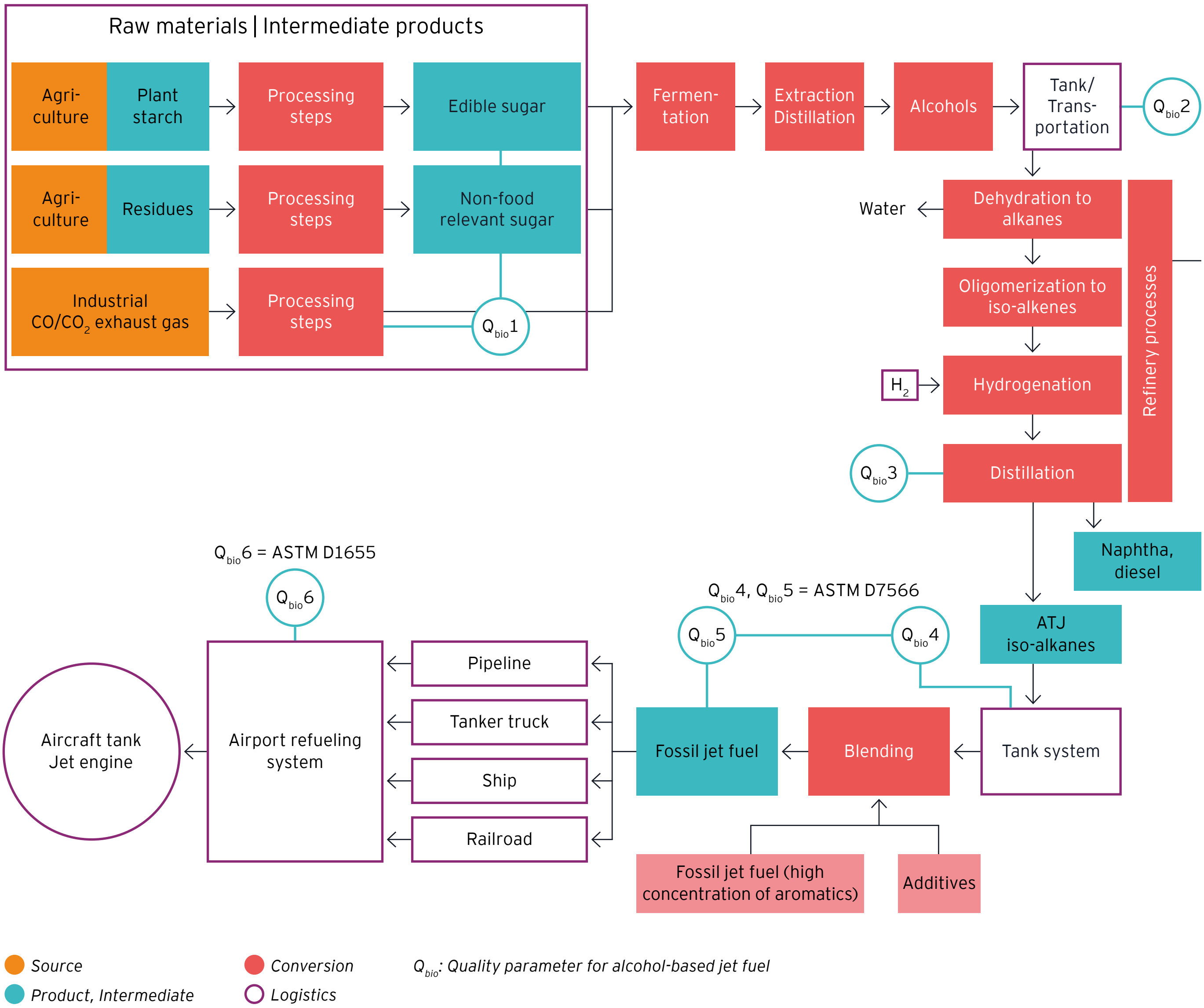
In the meantime, analogous routes based on drinkable ethanol and so-called fusel alcohols, which are also available through the fermentation of industrial waste gases from biomass, have also been certified.

The most commonly used synthesis sequence involves the elimination of water (dehydration) from alcohols, followed by oligomerization and hydrogenation with H_2. Alcohol-to-Jet Synthetic Parafinic Kerosene (ATJ- SPK) is separated from the diesel and naphtha fractions via distillation. ATJ processes have already been implemented by several companies on a production scale.

Figure 3

ATJ-SPK process route without "aromatics" generated in the process itself

(Source: Fraunhofer)



Q_{bio}: Quality parameter for alcohol-based jet fuel

The H_2 demand of plants designed for ATJ-SPK as the main product depends much more on the type of feedstock used than HEFA. Table 4 provides an overview of averaged H_2 requirements and the yield for a plant operated with ethanol or a plant operated with isobutanol and designed for ATJ-SPK.[8] In each case, pre-purified alcohols are fed from the point marked "$Q_{bio}2$" in Figure 3. At this point, only data and yields for edible sugars are shown because there is still no plant for the large-scale production of alcohols from non-edible sugars.

The data in Table 4 was determined by simulating industry-related data in ASPEN software and takes into account the specific challenge that arises for each alcohol type when linking the refinery processes shown in Figure 3. It should be noted that the carbon chain length and its distribution in the ATJ-SPK produced differ significantly depending on the alcohol type. Furthermore, very different quantities of naphtha and diesel are also produced. For the hydrogen (H_2) demand of a technology operated on industrial exhaust gases, no exact figures regarding the H_2 demand and yields are known. However, both certainly depend heavily on the ratio of the raw materials CO, CO_2, and possibly also the existing H_2 in the raw material, for example, in steel mill exhaust gases.

Table 4

Input and output "ATJ-SPK plant" in kilograms/ton alcohol type

(Source: Fraunhofer)

H_2 Input	ATJ-SPK Output	Diesel	Naphtha	Propane*	Others**	Alcohol type
5.9 kg	417.5 kg	119.3 kg	59.6 kg	0 kg	403.6 kg	Ethanol
7.5 kg	529.0 kg	0 kg	226.7 kg	0 kg	244.3 kg	Isobutanol

** Propane is generally not produced and is only listed as a comparison to HEFA*
*** "Other" includes H_2, light hydrocarbons and water vapor*

Process route 3: Bio-based SAF from synthesis gas (FT-SPK)

In this process route, synthesis gas is first produced by gasifying a diverse range of raw materials, which is then converted into SAF in several stages.[c]

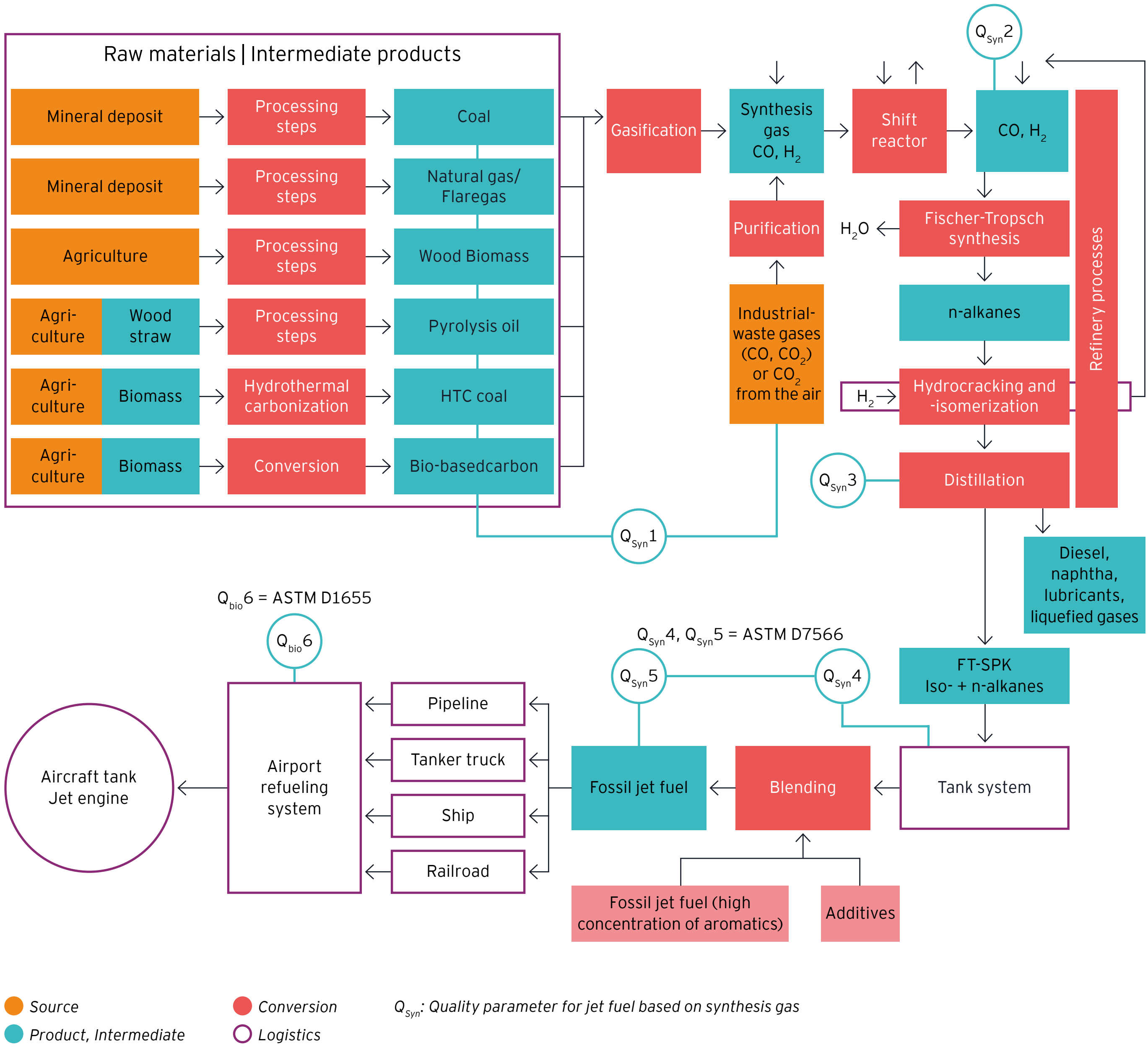
The first step is the thermochemical gasification of waste plastic or biomass such as willow wood, straw, wood chippings or wood chips, or "Black Liquor" from paper production into a synthesis gas. The tar contained in the synthesis gas is removed via a gas purification system together with dust and impurities. In the subsequent Fischer-Tropsch synthesis (FTS), the synthesis gas consisting of CO, CO_2 and H_2 is catalytically converted into long-chain hydrocarbons, often referred to as "FT Syncrude".

There are two basic realization options for this: the high-temperature FTS and the newer low- temperature FTS. In order to use the long-chain hydrocarbons formed (intermediate) as aviation fuel, subsequent hydro-cracking is required to increase the yield in order to convert long-chain hydrocarbons into diesel and kerosene. Finally, the product mixture is separated into aviation fuel and commercially available diesel, naphtha, lubricants and waxes, see Figure 4.

Aromatics are not normally formed during FTS but can be produced via a similar SKA process (Synthetic Kerosene Containing Aromatics).[9, 10] This product type is already specified and regulated in ASTM D7566.

c *Depending on the source material, these are referred to as gas-to-liquid (GtL, e.g., Shell), coal-to-liquid (CtL; the South African company Sasol is the leader here) or biomass-to-liquid (BtL; formerly e.g., the Choren process). Taken together, these processes are also referred to as the XtL process.*

Figure 4
FT-SPK process route
(Source: Fraunhofer)



In summary, no precise figures can be given for the H_2 requirement of the product mixtures produced from the range of raw materials shown. The yields depend heavily on the ratio of carbon to O_2 and H_2 in the raw materials as well as on the presence of other chemical elements.

This production method is known as "Direct Sugars to Hydrocarbons (DSHC)" or "Synthesized Iso-Paraffins (SIP) produced from hydroprocessed fermented sugars."

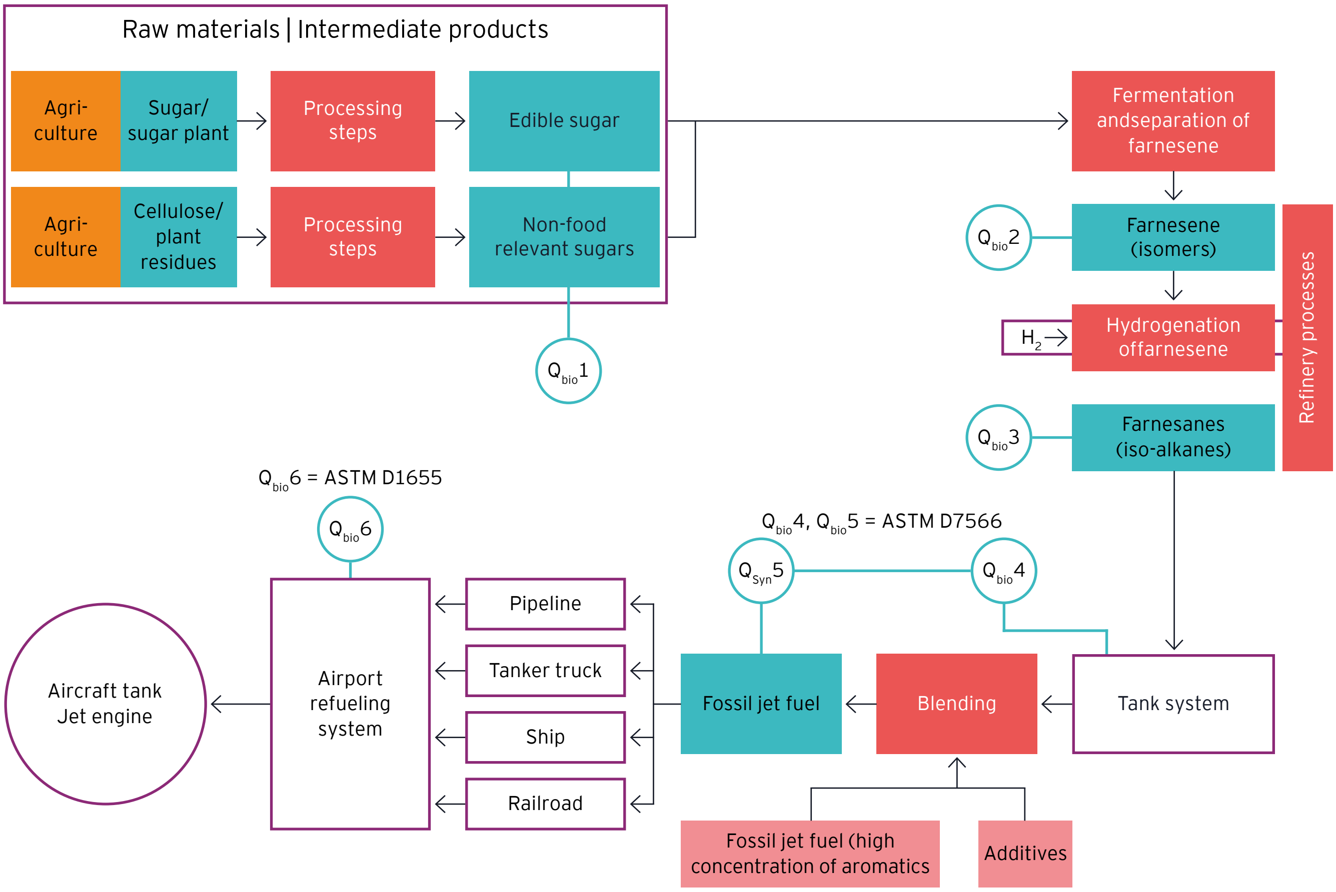
The process fermentatively converts sugar to the terpene "farnesene." This is further processed via a refinery process to isoalkanes as the final product, see Fig. 5. The product contains only a few molecular structures, so-called farnesanes, and only has a very narrow boiling distribution. Therefore, a maximum of 10% may be mixed or blended with fossil jet fuel.

Genetically modified microorganisms based on algae, bacteria or yeasts are used for fermentative conversion. Conventional sugar raw materials are currently used almost exclusively in this process, although sugars containing cellulose (e.g., sugar cane residues) have also been tested. The complexity and low efficiency of converting cellulosic sugars results in high raw material costs and excessive energy consumption. The H_2 requirement for this technology is not known.

Figure 5

DSHC/SIP process route

(Source: Fraunhofer)



Source

Product, Intermediate

Conversion

Logistics

Q_{bio}: Quality parameter for sugar-based jet fuel

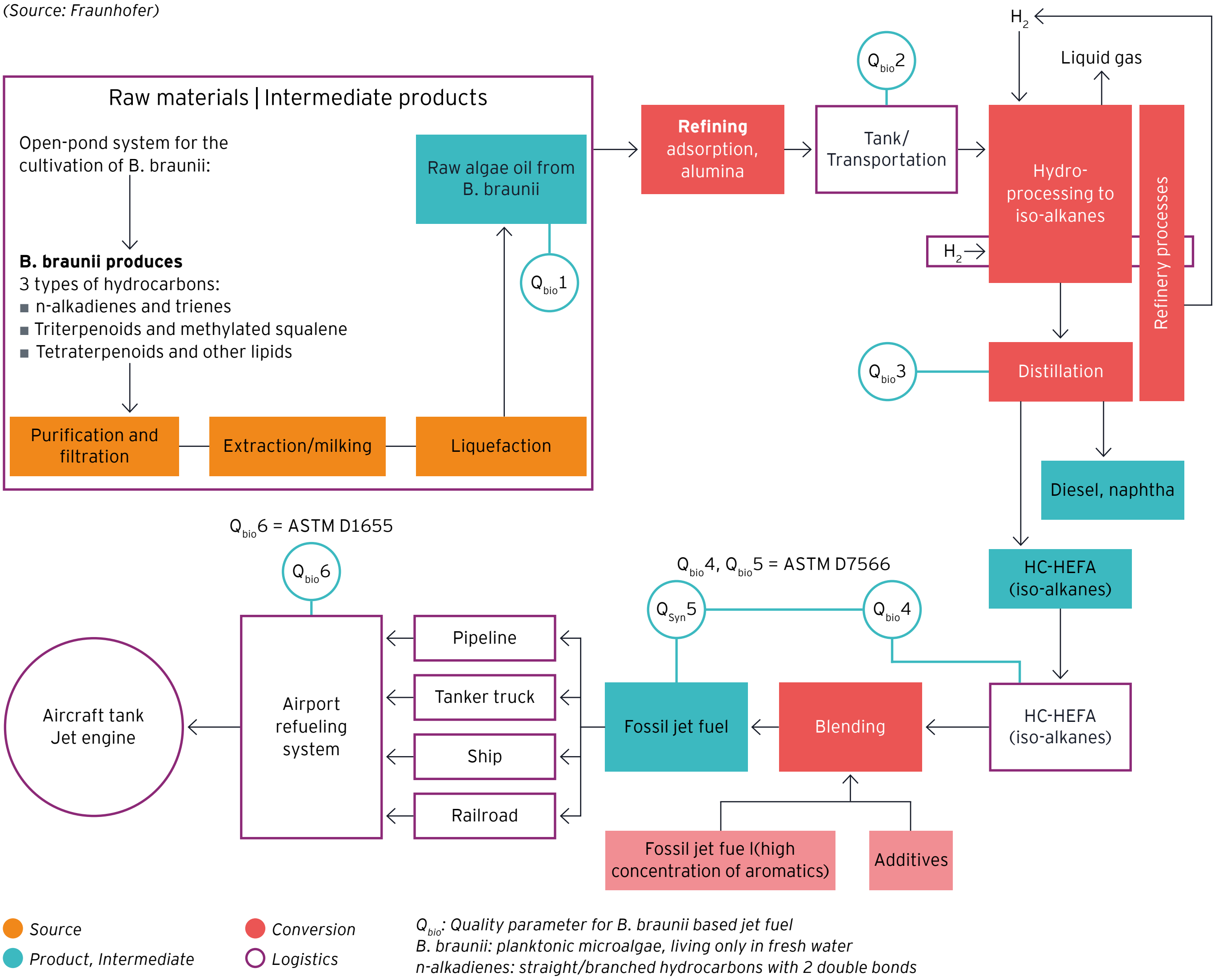
Process routes 5 and 6: Bio-based SAF from other raw materials (CHJ/HC-HEFA)
Other approved technologies for SAF production are catalytic hydro-thermolysis (CHJ, ASTM D7566 Annex 6) and hydrogenated hydro-carbons produced from a single type of algae (HC-HEFA, ASTM D7566 Annex 7).

In the CHJ process, also known as hydrothermal liquefaction, bio-based oil is mixed with FFA from the processing of used fats and oils with water and cracked at high pressure and temperature. Subsequently, the mixture is converted in multiple stages with H_2 into n-, iso- and cycloalkanes, as well as aromatic compounds. The product mixture has already been flown by the US Navy as 100% SAF, as the presence of of aromatics means that no fossil product needs to be added.[1] Nevertheless, its use for commercial aviation is currently only permitted as a 50% blend with fossil aircraft fuel. The process is like the HEFA process in Figure 2, but the "refining" process step was replaced by a non-catalytic cracking process, which also produces the aromatics.

According to literature references, only this cracking process has been technically integrated into an existing HEFA process at Montana Renewables in the USA as an alternative process step in "refining," but not the entire procedure.[11] The H_2 demand for this technology is not known.

HC-HEFA involves the conversion of the algae Botryococcus braunii (B. braunii) as the only type of algae approved for this process route. This is achieved through multi-stage hydroprocessing, i.e., multi-stage H_2 treatment steps to n- or isoalkanes, see Figure 6.[12]

Figure 6
HC-HEFA process route
(Source: Fraunhofer)



Q_{bio}: Quality parameter for B. braunii based jet fuel
B. braunii: planktonic microalgae, living only in fresh water
n-alkadienes: straight/branched hydrocarbons with 2 double bonds
Triterpenoids: large group of secondary metobolites in the plant kingdom
Tetraterpenoids: chemically modified tetraterpenes with oxygen groups

B. braunii produces hydrocarbons, which can be divided into three main groups:

1 | **n-alkadienes and trienes,**
2 | **triterpenoids and methylated squalene and**
3 | **Tetraterpenoids.**

In addition, other substances are also formed, including classic lipids and ether lipids. During the exponential growth of the algae, hydrocarbon and ether lipid productivity is at its highest. Like all photosynthetic microorganisms, algae require CO_2, light, inorganic nutrients and water. These requirements must be taken into account when cultivating algae in the Open Pond system. Due to the tolerance of algae to some pollutants, industrial flue gas can used to supply CO_2 to the cultures.

Purification into crude algae oil requires further pre-treatment steps. Centrifugation and filtration are carried out, for example by changing the pH, which leads to precipitation of the algae. Extraction solvents are used to obtain the hydrocarbons produced by the algae, which are located in the outer cell walls of the algae. Another possibility is extraction by means of CO_2 pressure adjustments. Fuels such as diesel, kerosene and naphtha have already been produced from algae crude oil in the past.[13]

According to the literature, the production of aviation fuels via hydroprocessing appears to take place essentially via hydrocracking, i.e., large molecules are converted into smaller ones in the kerosene boiling range.[14] One study emphasizes the potential advantage of using B. braunii algae as a raw material for fuels, as these can be obtained using non-destructive extraction technologies. Milking, in which the hydrocarbons are extracted from the algae cells without destroying the cells, eliminates the need for renewed cultivation, as is the case with agricultural raw materials. However, research is still required for the large-scale implementation and feasibility of these methods.[15] In 2021, the Japanese airline ANA flew on aircraft fuel mixed with microalgae (B. braunii) as part of the NEDO project. Despite such pilot projects, the use of B. braunii for the production of jet fuel is still at an early stage of development.[16] The H_2 requirement for this technology is not known.

Process route 7: Bio-based SAF with aromatics from alcohols (ATJ-SKA)
This recently approved technology for SAF production involves the fermentation of sugars from starch- and sugar-producing raw materials such as corn, sorghum, sugar cane or sugar beet as well as via the fermentation of cellulosic biomass, usually from lignocellulose hydrolysed with steam. Furthermore, biochemical conversion from H_2 and carbon monoxide, i.e., synthesis gas, is also permitted. The process may use a single alcohol stream with two to five carbon atoms, i.e. chemically speaking ethanol to pentanol, the mixtures of which are often referred to as fusel alcohols, as well as a combination of two or more ethanol to pentanol alcohol mixtures and process them together. On the one hand, a non-aromatic product is obtained via the process steps of dehydration, oligomerization, hydrogenation and distillation; on the other hand, an aromatic product is obtained via the process steps of dehydration, oligomerization, aromatization, hydrogenation and distillation[17, 5], which is significantly more similar to fossil aviation fuel than ATJ-SPK.[18] Technically, however, ATJ-SKA is a very similar process to SAF from alcohols (ATJ-SPK). Only the oligomerization process step in ATJ-SKA has been extended by the aromatization process step, so that the addition of aromatics produced from crude oil or the blending with fossil aviation fuel containing a lot of aromatics, in contrast to ATJ-SPK, is not mandatory. This is shown in Figure 3 with "Q_{bio}4."

The H_2 requirement for this technology is not known but should not differ significantly in magnitude from the ATJ-SPK technology.

Process route 8: Joint processing of biomass with crude oil (co-processing)
This method is referred to as co-processing, as both crude oil and biomass and coal-based alternative intermediate products are processed together in one refinery.

At present, the co-use of non-conventional raw materials in refineries is limited to fats and oils, fatty acids and fatty acid esters as well as Fischer-Tropsch intermediates, as currently permitted in ASTM D1655. The expansion of permissible alternative feedstocks through ASTM is already being worked on by several stakeholder groups.[6] Since refining processes are typically thermal, both the storage stability and thermal stability of feedstocks during heating are crucial and must be ensured through appropriate pretreatment steps. Additionally, the high O_2 content of bio-based oils must be considered, as O_2-containing products are formed during refining, and significantly more heat must be dissipated during the initial H_2 treatment step. Both factors usually require modifications or expansions to existing facilities, ultimately including additional quality control steps.

Fossil oils, like bio-based oils, can contain organic sulfur or nitrogen compounds, which the refinery is accustomed to treating. However, this is not the case for O_2 compounds. Fossil oil is virtually free of organic O_2 compounds. Therefore, for O_2-rich oils, a H_2 treatment (hydrotreating) must be added prior to the refining process. Figure 7 illustrates the principle and potential feedstocks for co-processing.

Figure 7
Co-processing in a refinery with options for fossil and renewable raw materials[19, 20]

Petroleum-based distillation cuts from a refinery and renewable raw materials for co-processing

Fossil raw materials
- Light and heavy as well as vacuum gas oil, kerosene

Renewable raw materials
- Fats and oils as well as Fischer-Tropsch intermediates

Processes

Refinery processes

Partially renewable products produced with co-processing
- Gasoline
- Diesel
- Aviation fuels
- Kerosene
- Naphtha
- Petroleum gas
- Other products

The H_2 need for co-processing is not known in detail and should not differ significantly from the requirement of HEFA, at least for fats and oils.

Refinery

1.1.2. E-SAF from CO_2: Power-to-Liquids (PtL)

The goal of using E-SAF is to close the carbon cycle, i.e., to prevent the introduction of fossil carbon into the active cycle. Ultimately, this means that all technical approaches to the production of renewable fuels must ensure that CO_2 is recycled as the ultimate end product of every use cascade of carbon-containing materials and brought into a new use cascade.

This also applies to all processes in which biogenic raw materials (biomass) are used: Biomass is primarily produced by photosynthetically active organisms, i.e. by plants or microorganisms. In photosynthesis, CO_2 and water are converted by solar energy (light) into carbohydrates, which ultimately serve to form biomass. At the beginning of every food chain is, therefore, the use of CO_2 as a carbon-containing raw material. In this respect, the production of biofuels also involves carbon capture and utilization (CCU) processes. In contrast to this natural use of CO_2 for the formation of biomass, the PtL approach focuses on the direct technical conversion of CO_2. The term CCU is generally only used for processes involving such technical use of CO_2.

The term CCU is generally used only for processes involving the technical utilization of CO_2.

E-SAF production routes always include at least one electrochemical process step, as the word "power" indicates in the term power-to-liquids. This is not about the technical use of electrical energy, such as for heating or cooling reactors or other plant components, but is stored in the form of energy-rich chemical compounds.

PtL products are chemical energy carriers that have been "electrically charged," so to speak, by electric current. In many E-SAF process routes, the electrochemical step involves the electrolysis of water, meaning the electrochemical splitting of water into H_2 and O_2, according to the following overall equation:

$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

H_2 is formed at the cathode by the reduction of protons:

$$2\,H^+ + 2\,e^- \rightarrow H_2$$

The chemical energy carrier H_2 is then used, for example, to build up energy-rich organic compounds, such as methanol or fuels, through chemical reaction with CO_2. In this way, electrical energy is used indirectly to reduce CO_2 by obtaining H_2 from water through electrochemical reduction, which then chemically reduces CO_2. As an alternative to this chemical charging of CO_2 with H_2, electrons can also be transferred directly from the electrode to a CO_2 molecule in an electrochemical reaction. In the so-called co-electrolysis of water and CO_2, H_2 (from water splitting) and CO (from CO_2 reduction) are obtained at the same time. Both products together form a mixture known as synthesis gas, which can be converted to SAF, e.g. via Fischer-Tropsch synthesis, as described further below in this section (see also 1.1.1, process route 3).

Another process for the electrochemical reduction of CO_2 provides the C_2 compound ethene (ethylene) as the targeted product.[21] In this process, the gaseous ethene forms on copper catalysts directly on the electrode surface and can then be further converted to SAF chemically after a gas purification step. This chemical conversion is an oligomerization[d], a linking of several ethene molecules in a theromcatalytic process (at high temperatures and over a solid catalyst bed).

This approach of a combined electro-thermocatalytic synthesis of fuels from CO_2 was successfully pursued, for example, in the EU-funded EcoFuel project.[22]

However, the present section focuses on the use of H_2 for chemical CO_2 reduction. There are various process routes that can be used to produce SAF from CO_2 as a primary carbon source.

Two different PtL production processes for SAF are currently on the way to commercial application, based on the chemical conversion of CO_2 by H_2, thereby delivering comparable SAF product mixtures, but differing in terms of specific conversion processes. These pathways are often referred to as the Fischer-Tropsch route and the methanol route. While the methanol route is still in the process of technical approval for use in aviation, the Fischer-Tropsch route is already approved according to the ASTM D7566 specification (see 1.2 for technical approval). This nomenclature of the Fischer-Tropsch and methanol routes is also used in this study. Both process routes are shown schematically in Figure 8.

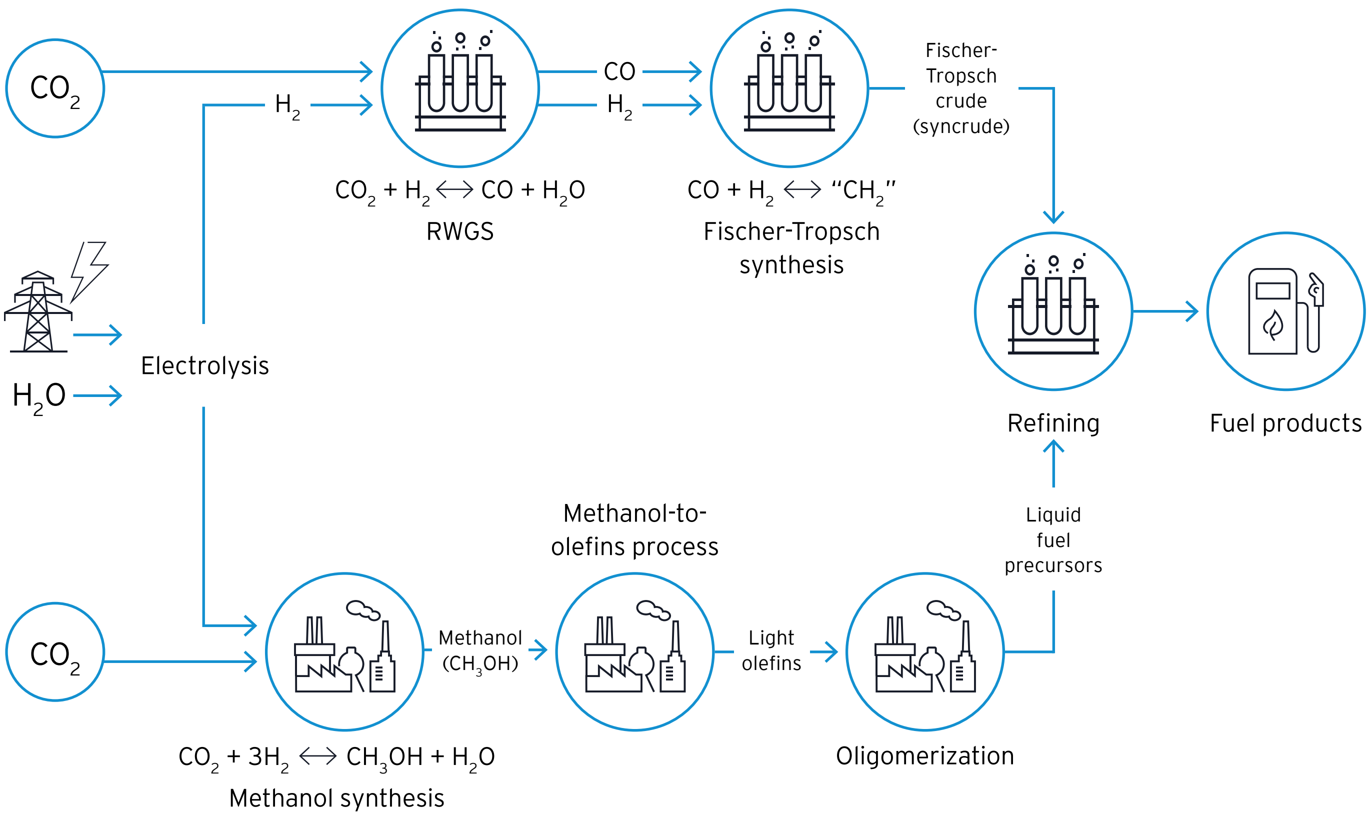
d In oligomerization, simply put, several molecules are chemically linked to form a larger molecule. The oligomer then consists of repeating units of oligomerized molecules. A high number of linked molecules are referred to as polymers.

> The availability of green energy and biogenic CO_2 will be crucial for the selection of potential regions for SAF production.

Air France-KLM Group

Figure 8

Schematic representation of the PtL process paths via the
1 | Fischer-Tropsch route (upper path) and via the
2 | Methanol route (lower path). RWGS: Reverse water gas shift.



Fischer-Tropsch synthesis (FTS)

The FTS is a process for converting synthesis gas, a mixture of H_2, CO and, to a lesser extent, CO_2, into product mixtures of liquid and solid hydrocarbons. The overall reaction is described by the following equation:

$$n\,CO + 2n\,H_2 \rightarrow (CH_2)_n + n\,H_2O$$

The hydrocarbons formed are expressed here as $(CH_2)_n$. The ratio of liquid to solid products can vary depending on process conditions. FTS was developed in the 1920s by Franz Fischer and Hans Tropsch in Mülheim, Germany, with the aim of producing gasoline from coal, as coal can be converted into synthesis gas through gasification. FTS is still used today in South Africa for coal liquefaction, where the technology has been operated on an industrial scale for many decades due to a lack of domestic oil resources alongside large coal reserves. Since synthesis gas can, in principle, be obtained through the gasification of many different fossil and biogenic raw materials, interest and application potential for FTS as a process for producing liquid hydrocarbons in the context of SAF have significantly increased in the last 10 to 15 years.

Technically, FTS is a heterogeneous catalytic process that operates at elevated temperatures (in the range 200°C–350°C) and pressures (up to around 25 bar) on iron or cobalt catalysts. A chain growth reaction takes place on the catalysts, in which the process conditions can be used to influence the product distribution (the distribution of products with different molecular masses). It is important to understand that the process does not yield a single chemical product, but rather, due to the statistical nature of chain growth reactions, always produces a mixture of products.

The FT crude product is a mixture of unbranched hydrocarbons, which may still contain unsaturated compounds and oxygenates[e]. To obtain SAF from the FT crude product (also known as Fischer-Tropsch crude), refining is required. Through the reaction with H_2, all oxygen atoms are removed from the raw product, and all double bonds are saturated. Finally, isomerization[f] must be performed to ensure that the product mixture no longer exclusively contains unbranched hydrocarbons, but alo a high share of branched compounds in the desired SAF range. The isomerization is crucial to ensure that the fuel remains in liquid state even at very low temperatures, such as those encountered at the cruising altitude of passenger aircraft.

With FTS, it is important to emphasize that the quality of the product mixture (chemical properties, product distribution, etc.) is independent of the actual raw material, i.e. the type of feedstock. This is because the raw material (coal, natural gas or even biogenic raw materials such as wood) is first gasified, converting it to synthesis gas. This synthesis gas is the feedstock for the FTS. As long as the composition and purity of the synthesis gas are adequately adjusted, it is completely irrelevant for the synthesis from which raw material it is generated. This is important because SAF produced via the FTS is approved for use in aviation in mixtures with fossil kerosene in accordance with ASTM D7566. This includes all production paths that run via the FTS, regardless of the actual raw material.

Methanol synthesis

In principle, the methanol route, like the FT route, involves the heterogeneous catalytic conversion of a H_2-rich synthesis gas into a liquid intermediate product, which is then further processed chemically to SAF. As schematically illustrated in Figure 8, the methanol route basically involves the following process steps: CO_2 is converted with H_2 to methanol. The reaction is selective and hardly any unwanted by- products are formed. Methanol is then reacted to light alkenes (also known as olefins), mainly ethene and propene. These gaseous alkenes are then oligomerized into liquid alkenes, mostly branched iso-alkenes. Finally, the liquid alkenes are hydro-genated to saturated hydrocarbons (alkanes) and fractionated by distillation.

FTS

e Organic compounds that contain oxygen atoms in addition to carbon and hydrogen atoms

f Isomers are chemical compounds that have the same atomic composition and the same molecular mass but differ in their spatial structure. Isomerization is when a compound is converted into another isomer. The composition (molecular formula) and molecular weight remain unchanged, but the molecular structure changes. In the above-mentioned case of isomerization, unbranched hydrocarbons are converted into branched hydrocarbons.

The following important differences to the Fischer-Tropsch route result from this simplified process description of the methanol route:

- The first process step, liquefaction, can be carried out directly by hydrogenating CO_2 – no prior conversion of CO_2 to CO is required. This conversion (reverse water gas shift, RWGS for short) according to the equation $CO_2 + H_2 \leftrightarrow CO + H_2O$ takes place at very high temperatures above 700°C and is both technically challenging and energy-intensive. The FTS, on the other hand, cannot be carried out directly with CO_2 and H_2, but requires a prior RWGS process.
- The liquefaction step does not directly deliver a hydrocarbon mixture like Fischer-Tropsch crude, but methanol, which is an alcohol. This intermediate product is already a highly relevant industrial platform chemical with a large and versatile market. However, SAF production still requires a multi-stage synthesis (via alkenes and oligomerization). The processing of methanol into SAF is therefore more complex than that of Fischer-Tropsch crude.

In both cases, comparable SAF products are obtained. In case of the methanol route, the fuel product has not yet been approved according to ASTM D7566. This is another difference from the Fischer-Tropsch (FT) route. However, a certification process for methanol-based SAF is already pending with ASTM. Therefore, it can be expected that approval will be granted soon.

CO_2 sources for E-SAF production
All PtL production routes begin with the provision of the raw materials, namely CO_2 and H_2. While H_2 is obtained in a renewable way, as mentioned above, primarily through electrolysis of water (electrolytic splitting of water into H_2 and oxygen), CO_2 can be provided from various sources. The easiest way to do this is by extracting it from industrial waste gas streams. These can be waste gases from fermentation processes, for example, in the production of ethanol. In biogas plants, a considerable amount of CO_2 is formed in addition to the target product methane (biogas contains around 40% CO_2), which must be separated during biogas purification before the methane can be fed into the natural gas grid. Another option is the incineration process of biogenic or fossil materials, for example in power plants and waste incineration plants. Cement plants are also often cited as major CO_2 emitters. Here, CO_2 is released through the combustion of natural gas to provide the required heat, for example, and through the burning of lime (calcination) according to the equation

$$CaCO_3 \rightarrow CaO + CO_2$$

At this point, it should be noted that truly renewable SAF production is only possible if the raw material CO_2 is also provided from a renewable source. This does not include the combustion of fossil fuels, such as natural gas or coal. Although it can be argued that the use of these exhaust gases is advantageous compared with direct emissions into the atmosphere, but this only applies as long as the combustion processes (e.g., a power plant) continue operation anyway. If the service life of such an incineration plant is extended by the subsequent use of the CO_2 produced, this is no longer a reasonable use case on the sense of sustainability.

The advantage of industrial CO_2 point sources lies in the comparatively high CO_2 concentration. Depending on the process, the CO_2 content of such gas streams can exceed 95%. Here, the CO_2 can be purified without great effort to such an extent that it can be used as a raw material in catalytic conversion processes. However, such point sources are not available everywhere, especially not in regions where renewable energy can be produced cheaply and on a large scale, such as in deserts or remote windy coastal regions. In these cases, either a CO_2 transport chain must be established or a process to directly extract CO_2 from the air is required (Direct Air Capture, short DAC).

DAC has the advantage that it can, in principle, be used anywhere in the world, independent of point sources. However, due to the low concentration of CO_2 in the atmosphere, the technical effort required is high.

DAC — direct capture of CO_2 from the air

Increasing CO_2 concentrations in the atmosphere and the resulting global warming are motivating the development of technical approaches to remove CO_2 from the air, to remove it permanently by sequestration in suitable rock formations or to use CO_2 as a raw material in the production of chemicals, materials or fuels. For this purpose, plants can serve as natural CO_2 scavengers that assimilate CO_2 through photosynthesis and bind the carbon in biomass. This biomass can then be used as a raw material or sequestered in underground storage facilities. Alternatively, CO_2 can also be captured from the air by technical means; this approach is known as direct air capture (DAC). The challenge here lies in the low CO_2 concentration in the atmosphere. Even though the atmosphere currently contains much more CO_2 than before the age of industrialization, the CO_2 concentration is actually quite low at around 425 ppm (0.04%) (Mauna Loa Observatory, Hawaii). Despite the high technical effort involved, DAC is seen by many as a key technology for harnessing CO_2 on a large scale or removing it from the atmosphere in the long term to keep global warming to a manageable level. The main reason for this is the high scalability of DAC, as the technology does not require any fertile arable land and CO_2 is present in the atmosphere in practically unlimited quantities. The working principle of DAC consists of the intake of air, the actual capture of CO_2 by a sorbent (a substance or a material to which the CO_2 is bound), the release of the bound CO_2 by regenerating the loaded sorbent (typically by heating) and the reloading of the regenerated sorbent. Following this working principle, there are various specific technical solutions, e.g., liquid vs. solid sorbent, active vs. passive air intake, etc., which are being developed by the various DAC companies. DAC is still a young business field, with pioneering companies such as Climeworks (Switzerland) and Carbon Engineering (Canada). The first and largest industrial DAC plant to date was commissioned by Climeworks in Iceland in 2021 and removes 4,000 tonnes of CO_2 from the atmosphere every year for the purpose of sequestration. A much larger DAC plant is currently being built in Texas based on Carbon Engineering's technology, which should be able to capture up to 500,000 tonnes of CO_2 per year. Technical DAC approaches therefore exist and have already been demonstrated on a large scale. The main challenge on the way to large-scale application lies in the high technical complexity and the resulting high costs. US$100 per tonne of CO_2 is often cited as the threshold for an economically attractive price for industrial use. However, such prices are not yet achievable with the current DAC plants; the costs are still several hundred dollars per ton. However, a significant reduction in costs is expected during a learning curve due to the increasing industrialization of DAC technology, so that CO_2 prices of less than US$100 per ton appear realistic.

1.2 Technical approval (ASTM) for Bio- and E-SAF

The evaluation and approval of bio- and E-SAF is defined and controlled by industry consensus- based fuel specifications overseen by the international aviation fuel industry. The process developed by the aviation fuel community is used by ASTM Subcommittee J to coordinate the evaluation of data and the establishment of specification criteria for new non-petroleum-based drop-in SAFs. Subcommittee J has published two standards to facilitate this process: ASTM D4054 "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives" and ASTM D7566 "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons." These standards are based on the airworthiness standards of the US-based Federal Aviation Administration (FAA) for the design of aircraft and engines, which regard the fuel as an operating restriction and not as a physical component of the product. As an operating restriction, the aviation fuels approved for use are only specified by the engine and aircraft manufacturer (the OEM) and are not created as part of the OEM's quality control system. This facilitates the handling of aviation fuel as an easily interchangeable commodity in a supply system where any fuel manufacturer can supply any aircraft with fuel.

ASTM D1655 describes the specifications for conventional aviation fuels.[23] Building on this, a standard for aviation fuels has been developed, which allows for the inclusion of up to 50 vol.-% synthetic hydrocarbons produced through blending. The blending is regulated by ASTM D7566.[17] Further blending components are under development and some are already ranked very high in the Fuel Readiness Level of the Commercial Aviation Alternative Fuels Initiative (CAAFI).[24] This is a measure of the development status of other fuel types. Various SAFs have already been developed, and the types of non-petroleum-derived aviation fuel approved by ASTM to date are shown in Table 5 below. This also includes the maximum blending ratio with conventional aircraft fuel and the date of approval ("Approval in Year").

Table 5

Timeline, types and blending limit of approved non-petroleum-based aviation fuels

(Source: Fraunhofer Umsicht)

Conversion process	Feedstock	Blend Ratio	Authorization	Operator TRL (7-9)
Fischer-Tropsch hydroprocessed synthetic paraffinic kerosene (FT-SPK)	Coal, natural gas, Biomass	50%	2009	Fulcrum BioEnergy, Kaidi, Sasol, Shell
Synthetic paraffinic kerosene from fats and oils (HEFA-SPK)	Vegetable oils and associated waste oils and fats, animal fats	50%	2011	Valero Energy Corp, World Energy Houston LLC, Honeywell UOP, Neste, Montana Renewables LLC (MRL), Chevron, ENI, TotalEnergies
Synthetic isoparaffins from hydro- processed fermented sugar (SIP)	Biomass for sugar production	10%	2014	TotalEnergies
Synthetic paraffinic kerosene plus aromatics (FT-SKP/A)	Coal, natural gas, Biomass	50%	2015	Sasol
Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)	Synthesis gas and bio mass via conversion to ethanol or Isobutanol	50%	2016	Gevo, Swedish Biofuels AB, LanzaTech Global

Conversion process	Feedstock	Blend Ratio	Authorization	Operator TRL (7–9)
Synthetic kerosene from hydro thermal conversion of fatty acid esters and fatty acids (CHJ)	Plant oils, animal fats, used cooking oil (with free fatty acids)	50%	2020	Applied Research Associates (ARA)
Synthetic paraffinic kerosene from hydroprocessed hydrocarbons esters and fatty acids (HC-HEFA)	Terpenes of the algae Botryococcus braunii	10%	2018	IHI corporation
Alcohol-to-jet synthetic kerosene with aromatics (ATJ-SKA)	Synthesis gas and Biomass via conversion to C_2- to C_5-alcohols	50%	2023	Swedish Biofuels AB, LanzaTech Global
Co-hydroprocessing from Fischer- Tropsch hydrocarbons and O_2-containing intermediates in a conventional oil refinery (co-processed SAF)	Fischer-Tropsch hydrocarbons, cover-valued with crude oil	5%	2020	Fulcrum BioEnergy
Co-hydroprocessing of esters and fatty acids in a conventional oil refinery (co-processed SAF)	Hydrocarbons from fats and oils, cover-valued with crude oil	5%; however, 30% is technically possible[25]	2020	BP, TotalEnergies, Repsol, OMV, ENI, Preem

In the supply chain, aviation fuel is transported near other types of fuel, where it is exposed to possible mixing and contamination with other non-aviation fuels such as diesel and gasoline. As aviation fuel is traded as a commodity, ownership of batches of fuel can change hands several times en route to the airport. Given this distribution system and the potentially changing nature of liquid fuels, FAA regulations are aimed at the endpoint of the supply chain — the aircraft. The regulations require the aircraft and engine manufacturer to specify fuels that are approved for use on the aircraft and require the aircraft operator or airline to use only the fuels listed by the manufacturer.

Due to concerns about the security of supply and the environmental impact of petroleum, the aviation fuel community founded CAAFI in 2006 to promote the development and use of SAF. One of the most important initial decisions made by the organizers was to restrict the use of SAF to drop-in aviation fuels. These fuels are defined as having essentially the same properties and composition as the petroleum-derived aviation fuel used by today's fleet of commercial and military aircrafts. Only SAFs that are compatible with the existing aircraft fleet and the infrastructure for aviation fuel distribution are considered to be essentially identical aviation fuels. Therefore, no special official approval is required for the use of these fuels. The qualification process for SAFs is initially based on the technical review of the engine and aircraft manufacturers to determine whether an SAF is suitable for use. More detailed tests are then carried out. ASTM D4054 describes the testing and evaluation program developed by members of the ASTM Aviation Fuels Subcommittee to compare the properties and performance of SAFs with those derived from petroleum. If a SAF is essentially identical to petroleum-derived fuels, it can be included in the ASTM D7566 specification.

ASTM D4054 is intended as a guide, not a regulation. It provides the SAF manufacturer with information on the tests and property objectives required for evaluation. D4054 represents an iterative process and requires SAF developers to provide fuel samples, measure their properties, composition, and performance, and then regularly review the results in collaboration with key stakeholders in the aviation fuel industry, as well as engine and aircraft manufacturers. These reviews usually lead to questions and comments that may result in the need for additional testing. The review comprises four tiers, which are described in Table 6.[26]

Table 6

Qualification process for SAF according to ASTM D4054[26]

Tier 1: Basic specification properties	Level 1 testing requirements are typically inexpensive (approximately US$5,000, ASTM 2018) and require less than 40 liters of SAF (0.03 tonnes).
Tier 2: Usable properties	The specification properties tested at Stage 1 represent a subset of the properties of an aviation fuel that must be controlled to ensure safe and proper aircraft and engine operation. These properties, referred to as FFP (Fit for Purpose) properties, are not routinely measured for conventional fossil aviation fuels from the refinery as they are constant. However, these properties must be measured for fuels produced from alternative feedstocks. These level 2 tests cost up to US$50,000 and can measure up to 400 liters of fuel. (0.32 million tonnes) of fuel (ASTM 2018).
Tier 3: Testing of engine/aircraft systems and components	The scope of Tier-3 and Tier-4 testing is based on the evaluation of Tier-1 and Tier-2 data. Due to the complexity and advanced technology of modern gas turbine engines and aircraft, the ASTM committee relies on the expertise of aircraft and engine manufacturers to determine the scope of testing. Tier 3 and Tier 4 testing typically requires the use of specialized OEM equipment, facilities and equipment. The fuel required for these tests can range from 1,000 to 60,000 liters (0.79 and 47.58 tonnes). The costs amount up to US$1.5 million. Tier 3 includes tests for compatibility with engine elements, coatings and metals as well as fuel system tests such as acceptance testing of fuel components under cold operating conditions. Typical tests also include cold start, high altitude and low power lean burn, turbine inlet temperature distribution measurements and gas and smoke emissions.
Tier 4: Large-scale engine tests or flight tests	Large-scale engine testing may be required to evaluate performance operability, emissions or long-term durability when operating with SAF. These tests can require up to 750,000 liters (594.75 tonnes) of fuel and up to US$1 million (ASTM, 2018). Emission tests can usually be carried out at the same time as other engine tests. Flight tests are usually not required.
ASTM D4054, Fast-track process	It was agreed that only reduced testing requirements can be imposed on manufacturers of new SAFs that fall within the range of a typical conventional aviation fuel in terms of composition and performance. These were included in ASTM D4054 as Annex A4 in September 2020 and are referred to as fast-track procedures. However, the reduced test requirements are accompanied by a maximum blending limit of 10%.

Regulatory framework

> "Although the EU has set concrete minimum blending quotas for SAF in the EU with the ‚ReFuelEU Aviation' regulation from 2025 and beyond to promote the SAF ramp-up, there are considerable doubts as to whether these objectives will be achieved without further political support. In order for Europe to remain attractive as a production location for SAF, the regulatory framework conditions must be adapted in an investment-friendly and binding manner in the long term.

Melanie Form, Member of the Management Board and Managing Director, Aireg

Introduction and summary of the chapter

In Europe, there are many measures and policy initiatives aimed at achieving the objective of climate neutrality by 2050. This concept of climate neutrality or the net-zero target is a scientific principle that was established by the EU as a central climate objective as part of the European Green Deal presented in 2019.[27] This deal is a response to the Paris Climate Agreement and its objective of limiting global warming to a maximum of 1.5 °C compared with pre-industrial levels.[28] The vision is the sustainable transformation of the EU economy.

To achieve this climate target, the concept of climate neutrality must be implemented in a meaningful way. This requires an individual decarbonization strategy at national, subnational, corporate and organizational levels.[29]

The reduction of greenhouse gas emissions and the achievement of climate neutrality are consistently based on voluntary political commitments. It is important to point out that governments, companies and NGOs must take concrete measures to achieve their objectives. Such objectives require a political framework for the use of low-carbon technologies and effective emission avoidance strategies and, in many cases, cooperation with citizens.

The Green Deal includes a broad range of measures that affect all sectors of the economy, including the aviation industry. The EU provides extensive financial support, for example, for research and innovation in low-carbon aviation, the promotion of the use of SAF and the establishment of the European Investment Fund to support more climate-friendly companies in the aviation industry.

The EU Green Deal also includes various initiatives, for example the EU ETS, the EU Renewable Energy Directives (RED II and RED III) and the ReFuelEU Aviation. These initiatives aim to reduce greenhouse gas emissions, promote renewable energy and put the aviation industry on a sustainable course. They also include binding objectives and legal frameworks to achieve these goals by 2030 and beyond. The result should be attractive framework conditions for the development of renewable energy sources (e.g., green H_2) and their derivatives (e.g., e-fuels) in the EU. The ReFuelEU Aviation Initiative aims to ensure fair competition in sustainable aviation and promote the reduction of emissions by expanding the use of SAF. It provides binding SAF quotas from 2025 that apply to aviation fuel supplied at EU airports.

Among other things, there are mechanisms for airlines in the EU to bring the implementation of climate protection measures. For example, CO_2 emissions from the aviation sector have been integrated into the EU ETS since 2012. So far, 17 million tonnes of CO_2 per year have been saved in the aviation sector with the help of this system. It is also possible to impose penalties to oblige companies to comply with their emission reduction objectives. The aviation industry is also aiming to manage the "green premium," to reduce the price difference between conventional kerosene and SAF. Globally, there are a variety of approaches to reducing carbon emissions, depending on the political preferences and prosperity of each country. The creation of a globally uniform carbon price is made much more difficult by varying pricing policies and local initiatives.

Existing gaps in the structure must be addressed in order to achieve full integration of aviation into climate policy. This includes a standardized collection of emissions data from aviation, agreement on a global approach to emissions reduction and binding mechanisms to enforce this approach.

Advances in technology development and cooperation between regulators and companies could help to overcome these challenges and create a low-carbon aviation industry.

The following chapter discusses global and European aviation regulations and directives as well as the measures to be taken in the event of a breach. It also identifies gaps in the current regulatory framework and concludes by explaining why a reduction in CO_2 emissions alone is not enough to minimize the impact of flying on the climate.

"

There are still several obstacles to the regulation of sustainable aviation fuels, which is delaying or preventing major investments in SAF. For Germany and Europe to establish themselves as attractive SAF production locations, the fastest possible development must be achieved. The regulatory framework conditions must be industry-friendly and binding in the long term. In addition, investment incentives must be created and long-term support programs introduced.

Melanie Form, Member of the Management Board and Managing Director, Aireg

2.1 Regulatory framework conditions at European and global level

There are a wide range of measures and political initiatives in Europe to achieve the objective of net zero by 2050. One important EU strategy is the European Green Deal, which was presented by the EU Commission in 2019. Its objective is to transform the EU economy in a sustainable way. The central focus is to achieve climate neutrality by 2050, with clear support for research and innovation for low-carbon aviation and the promotion of the use of SAF.[30] The EU Green Deal includes the following initiatives, among others:

- **European climate law** with the objective of becoming climate-neutral by 2050: By 2030, emissions are to be reduced by at least 55% compared to 1990 levels. The law sets out the legal framework for achieving these targets.

- **European industrial strategy** that supports the EU industry in terms of change, innovation and growth with a view to the green and digital transformation:[30] It has an impact on the EU's industrial ecosystems, including the aviation, space and defense industries.[31]

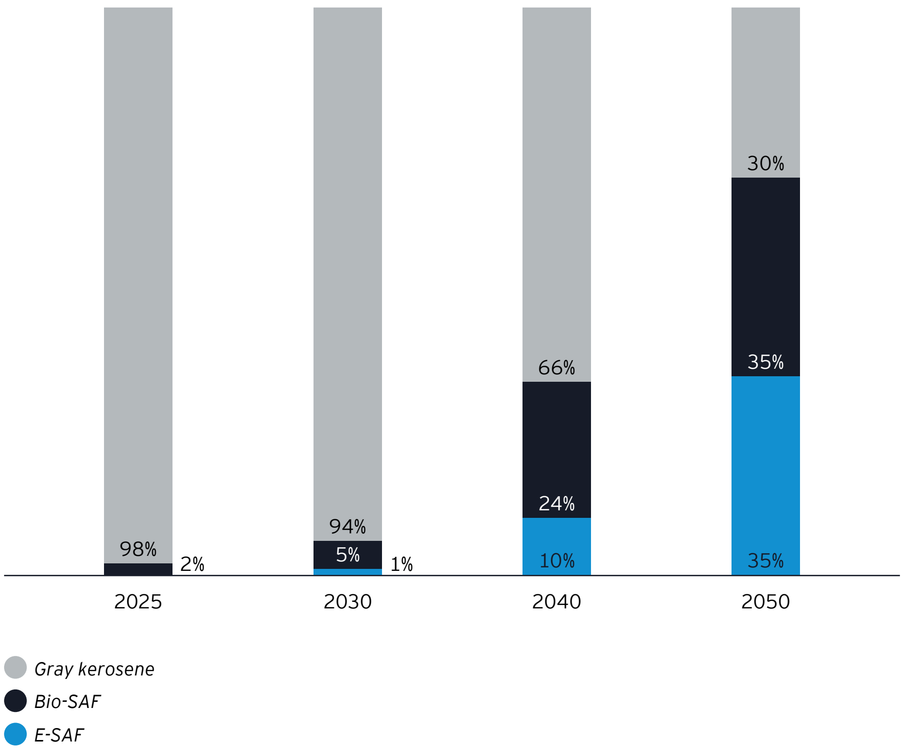
- **The "Fit for 55" package** aims to reduce greenhouse gas emissions by 55% by 2030 and achieve climate neutrality; it contains concrete measures, proposals and laws. Part of this is the ReFuelEU Aviation Initiative founded in September 2023, which obliges aviation fuel suppliers to supply airports with SAF in future. The EU ETS was also reformed through the Fit for 55 package.[1] The revision of RED II and the development of RED III are also an important initiative of the Fit for 55 package.[32]

> It will be a challenge for airlines to meet the ReFuelEU quotas. As a result, some players are trying to abolish them. However, we recognize the need for these quotas and hope to maintain them in the long term. SAF quotas are essential for the decarbonization of the aviation sector.
>
> **Dr. Mark Misselhorn,** Chief Executive Officer, Caphenia GmbH

The ReFuelEU Aviation Regulation mandates a minimum share of SAF starting in 2025, and a minimum share of E-SAF starting in 2030, which must be included in the fuel available at EU airports and gradually increased until 2050 (reaching at least 70% SAF by 2050).[33] The goal is for SAF to constitute more than half of the fuel at airports by 2050, with increased direct flight routes and incentives for SAF within the EU trading system.[34] The planned shares (see Figure 9) are effective as of January 1, 2024. It is important to note that, in the absence of a specific SAF specification, it is assumed that bio-based SAF will be used. Since bio-based SAF is currently more cost-effective and available in larger quantities, its use is more likely than E-SAF.[34]

Figure 9

Percentage of SAF in aviation fuel[35]



The ReFuelEU Regulation also aims to change current refueling practices in Europe. Aircraft operators often refuel with larger quantities of fuel than necessary to avoid expensive refueling abroad, which leads to higher emissions. To counteract this, the regulation requires aircraft operators to ensure that, starting from January 2025, the amount of aviation fuel taken on at a specific EU airport annually corresponds to at least 90% of the amount refueled annually[35]. This means that aircraft operators must refuel their planes at European airports accordingly, making cost-saving measures through excessive refueling abroad no longer sensible. If the SAF quotas are not reached, the parties involved must pay fines.[36]

For **aviation fuel suppliers,** the minimum penalties are equal to twice the difference between the price of SAF and the price of conventional kerosene per metric ton multiplied by the amount of aviation fuel that does not meet the quota.[37]

Penalty =
2 × [Price SAF (per ton)
− Price of conventional kerosene (per tonne)]
× Quantity of aviation fuel that does not meet the quota (per year)

For **aircraft operators,** the minimum penalty is twice the annual average price of aviation fuel per tonne multiplied by the annual amount not refueled. For EU airports, the penalties should be defined and structured by the Member States.[37]

Penalty =
2 × [average price of conventional kerosene (per year)
× quantity of SAF not refueled (per year)]

The **EU ETS** aims to reduce emissions across various industrial and energy sectors by allowing companies in the energy and energy-intensive industries to buy and sell emissions allowances. Since 2012, airlines have been included in the emissions trading system with CO_2 certificates, requiring all airlines operating in Europe to monitor, disclose, and verify their emissions. Airlines are allocated a set number of CO_2 certificates, which allow them to offset corresponding amounts of CO_2 emissions. If an airline exceeds its allocated emissions allowance, it must purchase additional certificates or face financial penalties. Since 2017, the scope of the ETS has been limited to flights within the European Economic Area (EEA), whereas it previously also covered flights to and from EEA airports. So far, the EU ETS has contributed to a reduction of 17 million tons of CO_2 emissions per year in the aviation sector.[38]

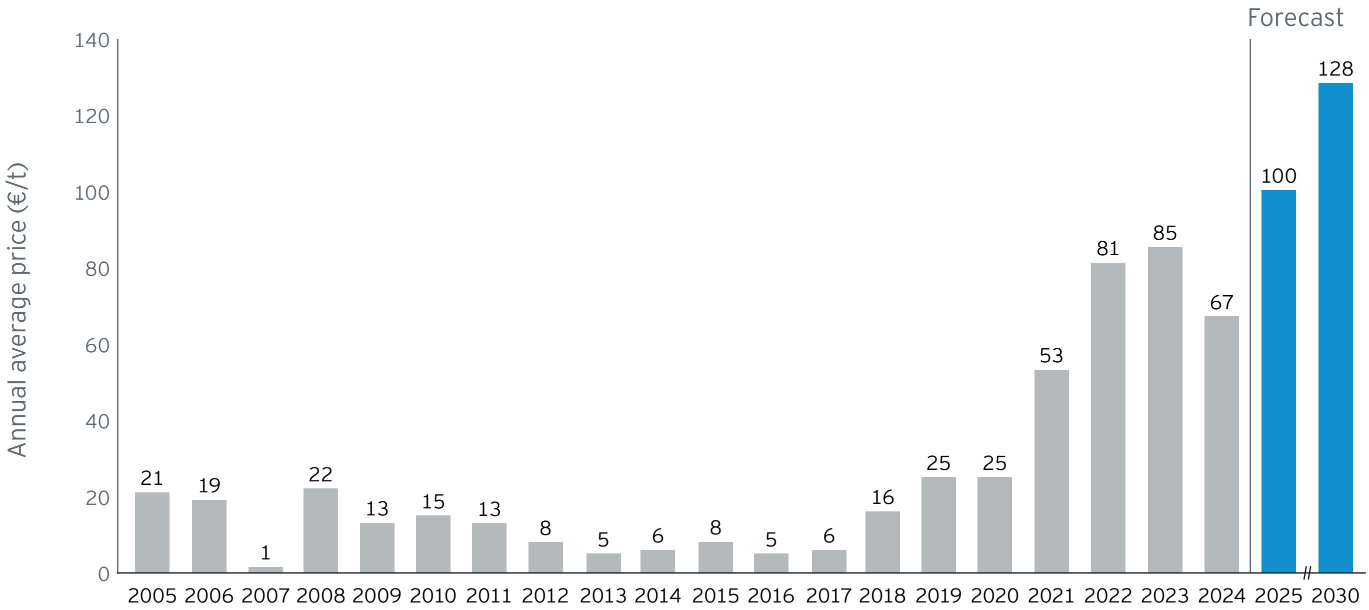
Emissions allowances are traded using either the cap-and-trade or the baseline-and-credit system. Under this approach, a fixed upper limit for emissions is set and the emission allowances are either auctioned or allocated free of charge according to certain criteria. In contrast, the baseline-and-credit system does not set a fixed limit for emissions but creates incentives for polluters to reduce their emissions beyond the expected reduction obligations. This allows them to earn credits and in turn sell them to other companies that need them to comply with the regulations that apply to them.[39]

> "The ReFuelEU Aviation Initiative's 2% quota is a positive start. However, a more ambitious initial quota of 5% would have desirable results. In view of the limited market availability, a lower quota is understandable.

Jan Eike Blohme-Hardegen, Head of the Environmental Department, Hamburg Airport

Figure 10

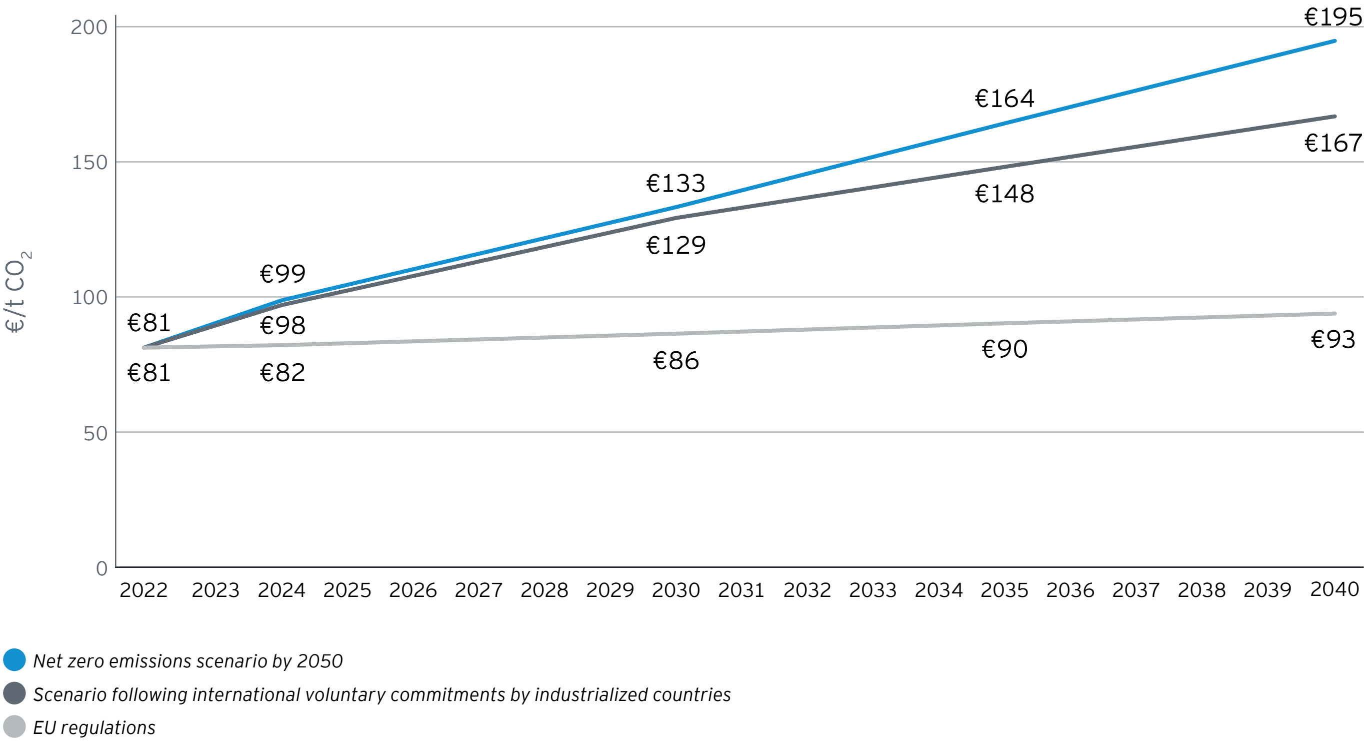
Overview of the price increase per certificate[41]



The EU ETS is based on the cap-and-trade system creating economic incentives for companies and countries to sell credits and thereby reduce emissions, which in turn has a positive impact on the environment. The price for the certificates is set voluntary on the market. Political decisions can influence the price by reducing or limiting the number of available certificates. Prices depend on political measures and regulations to reduce emissions and the competitiveness of renewable energy sources.[40] It is expected that the price of emission certificates will rise. Due to the Fit for 55 package and the energy crisis because of the current Russia-Ukraine conflict, the EU carbon price of allowances in 2022 was around €82/tonne (~US$81/tonne) CO_2. It is estimated that the price of carbon allowances in the EU will rise to over €100/tonne (~US$103/tonne) CO_2 from 2025. This increase is supported by the EU's enhanced political climate policy (Net-Zero Emissions Trading). [41]

According to this forecast, the price per certificate will rise steadily and reach over €120 (~US$123) in 2030. These changes will highly dependent on the CO_2 market. A CO_2 price forecast also depends on various factors (economic growth, government policy, technological progress, costs of alternative energy sources), so this forecast should be viewed with caution. Figure 11 shows price development of green CO_2. A distinction is made between three scenarios, which clearly show that stricter climate policies lead to significantly higher CO_2 prices. It is assumed that countries without carbon pricing use a variety of approaches to reduce carbon emissions. These depend on the country's political preferences and prosperity.[41]

Figure 11
EU CO_2 price forecast
(Source: IEA)



The EU's Renewable Energy Directive II (RED II) from 2018 has the objective of covering 32% of energy consumption from renewable sources by 2030. It prescribes the consumption of biofuels (including Bio-SAF) and biogas.[42] The list of biofuel feedstocks contained in Annex IX, Part A (feedstock sources without a cap) and Part B (feedstock sources with a cap) must be regularly reviewed by the EU Commission with regard to the addition of feedstocks that meet the criteria set out in Article 28(6).[43] The new raw material sources should make it possible to produce several million tonnes of SAF without building entirely new production plants. This applies particularly to HEFA/HVO and ATJ, as well as co-processing. Since March 2024, there has been a regulation regarding the new raw material sources specifically for SAF in the Annex I, Part A approved raw materials. This was already transposed into national law in Germany in April 2024 and will apply from July 2024.[44]

The EU's Renewable Energy Directive III (RED III/2023) was developed as a revision of RED II. In order to achieve the emissions reduction target of 55% by 2030, it was decided that the share of renewable should be increased to 42.5% of total EU energy consumption by 2030. By this time, member states must either achieve a 14.5% reduction in greenhouse gas intensity in the transport sector through the use of renewable energies or have a share of at least 29% renewable energies in final energy consumption in the transport sector.

A sub-target of 5.5% advanced biofuels (generally non-food based) and renewable fuels of non-biological origin (mainly green H_2 and e-fuels) for the share of renewable energy in the transport sector is also set. As part of this objective, a minimum share of 1% of renewable fuels of non-biological origin in the supply of renewable energy to the transport sector in 2030 is prescribed.[45] The directive must be transposed into national law within 18 months of its entry into force.[46] Nevertheless, the provisions of the directive must be transposed into national law by the Member States by 21 May 2025, subject to individual provisions.[47] From summer 2025, the EU ecolabel for flights will continue to be awarded voluntarily.[48]

The objective is to reduce the environmental footprint of aviation by providing trustworthy, understandable, reliable and standardized information to influence passengers to choose sustainable flight options. This is based on existing standards (EU ETS, ReFuelEU), data and best practices and takes transparency, simplification, comprehensiveness and voluntariness as a basis.[49] The following three label categories are defined: "Flight Label," "Airline Label" and "Aircraft Label."[50]

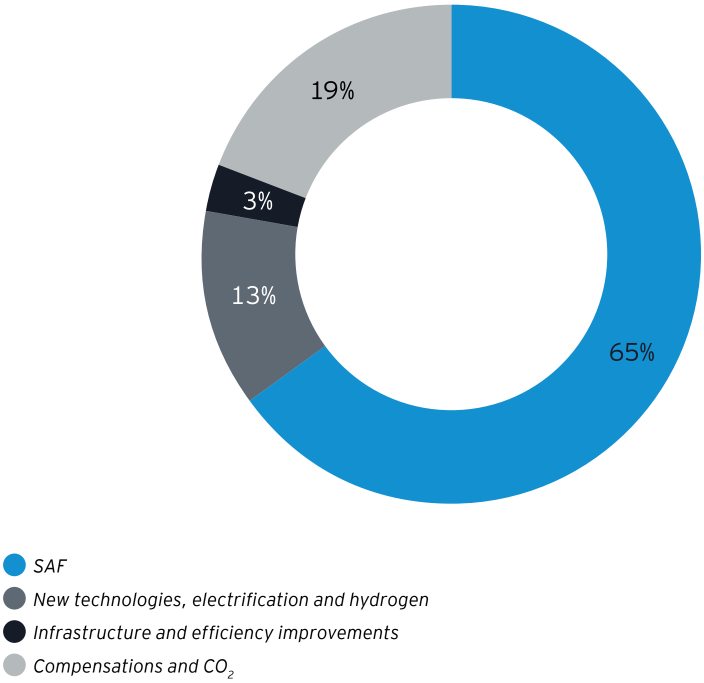
The following regulatory mechanisms are defined at international level, for example:

- **Sustainable Aviation Fuel certificates** (SAFc) and Clean Skies for Tomorrow (CST). The SAFc system, developed by the World Economic Forums' (WEF) CST initiative, aims to reduce emissions in the aviation sector by the use of SAF. The scheme allows travelers and companies to claim emission reductions by the cost premium for SAF. Originally aimed at business travel, the SAFc is designed to stimulate demand for SAF and generate additional funds for its production. The system is linked to the book-and-claim, which ensures that aviation fuel is delivered to an airport closest to the production site but that the certificate is validated at other locations.[50]
- **IATA's Emissions Reduction Roadmap.** IATA sets international standards for many areas of air transport, including safety and operational standards, flight bookings and travel agency practices, as well as measures to reduce emissions by airlines. IATA is developing its own strategy to achieve the global net-zero objective for the aviation sector by 2050, with SAF contributing around 65% of the necessary emissions reduction (see Figure 12). The strategy is not binding but is recommendatory.
- In the long term, IATA's objective is to move away from compensation measures (offsetting[g]) and instead focus more on the use of SAF. IATA emphasizes the need for close cooperation between industry and governments to achieve climate neutrality.[51] As part of the Energy and New Fuels Infrastructure Net Zero Road Map, it recommends scaling SAF production to over 400 million tonnes/year in order to achieve the industry's net-zero objective.[52]

Figure 12

IATA's strategic net-zero objectives

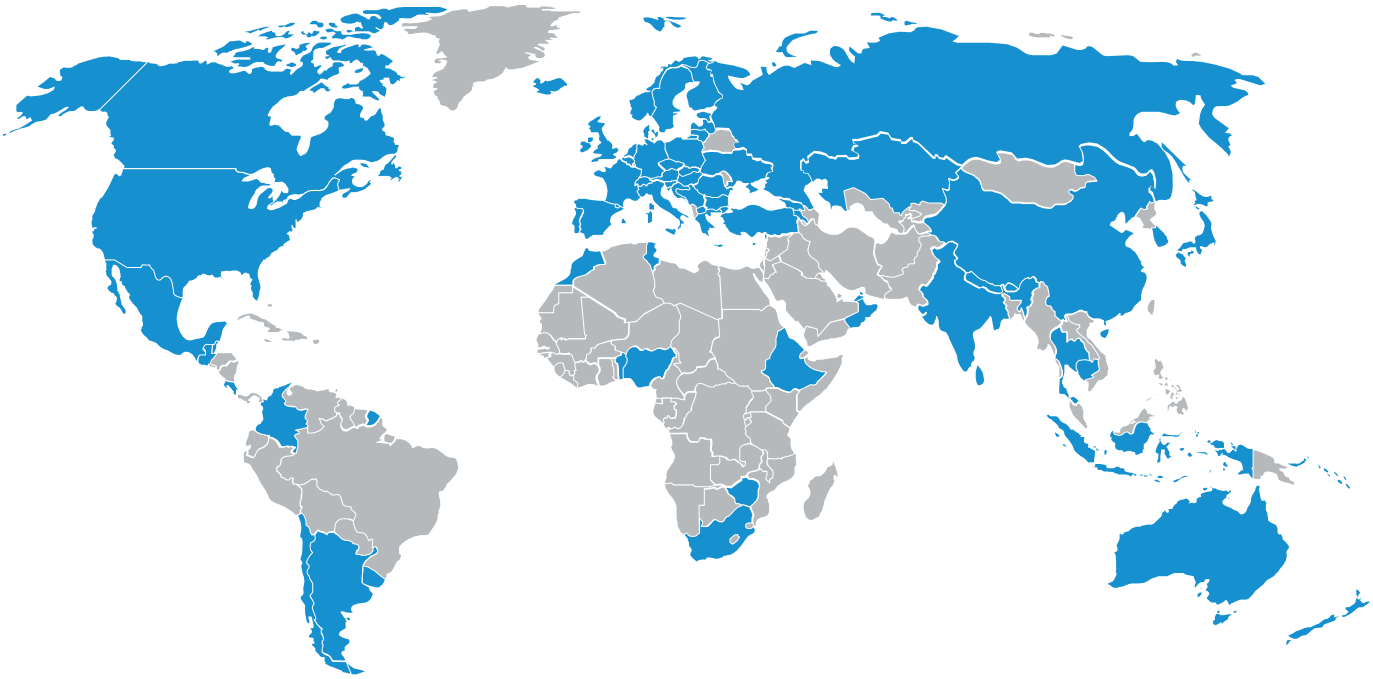
(Source: IATA)



g Offsetting is the process of compensating for the amount of CO_2 produced by promoting renewable energy or financing sustainable initiatives. The financing of sustainable initiatives is often through the purchase of so-called certificates, whereby companies buy specific certificates. Offsetting is a controversial concept, as there is no guarantee that the initiatives' measures are actually necessary. Companies often purchase certificates for initiatives that are not exposed to any threat at all. As a result, there is a risk of ultimately greenwashing and not actually offsetting CO_2.

Figure 13

Overview of established sustainable strategies under the Paris Agreement[53]



- **National sustainability strategies:** At present, 75 countries have already developed and communicated sustainable long-term strategies under the Paris Agreement to limit greenhouse gas emissions. The countries highlighted in gray have not yet provided any information (Figure 13). These strategic objectives often also relate to air traffic.
- **Green premium** as a price difference between the conventional kerosene price and the SAF price:[54] This difference is paid by passengers. There are several measures that can reduce or prevent the green premium. The expansion of SAF technologies can lower production costs while creating access to more raw materials and facilities in different locations. Furthermore, regulations can ensure that the additional costs are shared fairly among all parties involved.[55]

There are also various emissions trading systems at the global level, for example:

- **International aviation agreement –** ICAO CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). The ICAO CORSIA system is a global emissions trading system for the aviation sector. The system was agreed upon in 2016 and has been mandatory for large aviation companies since 2021. Participants must offset a certain amount of CO_2 emissions by purchasing emission rights from sectors other than the aviation industry.

Figure 14

CORSIA system overview[56]

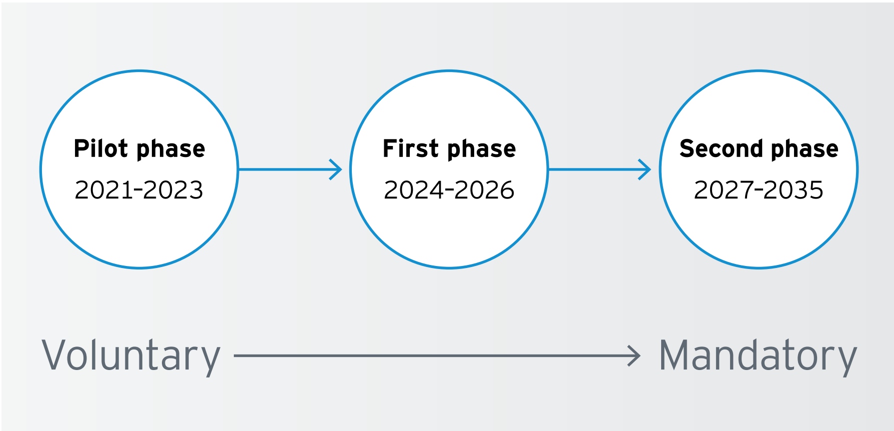
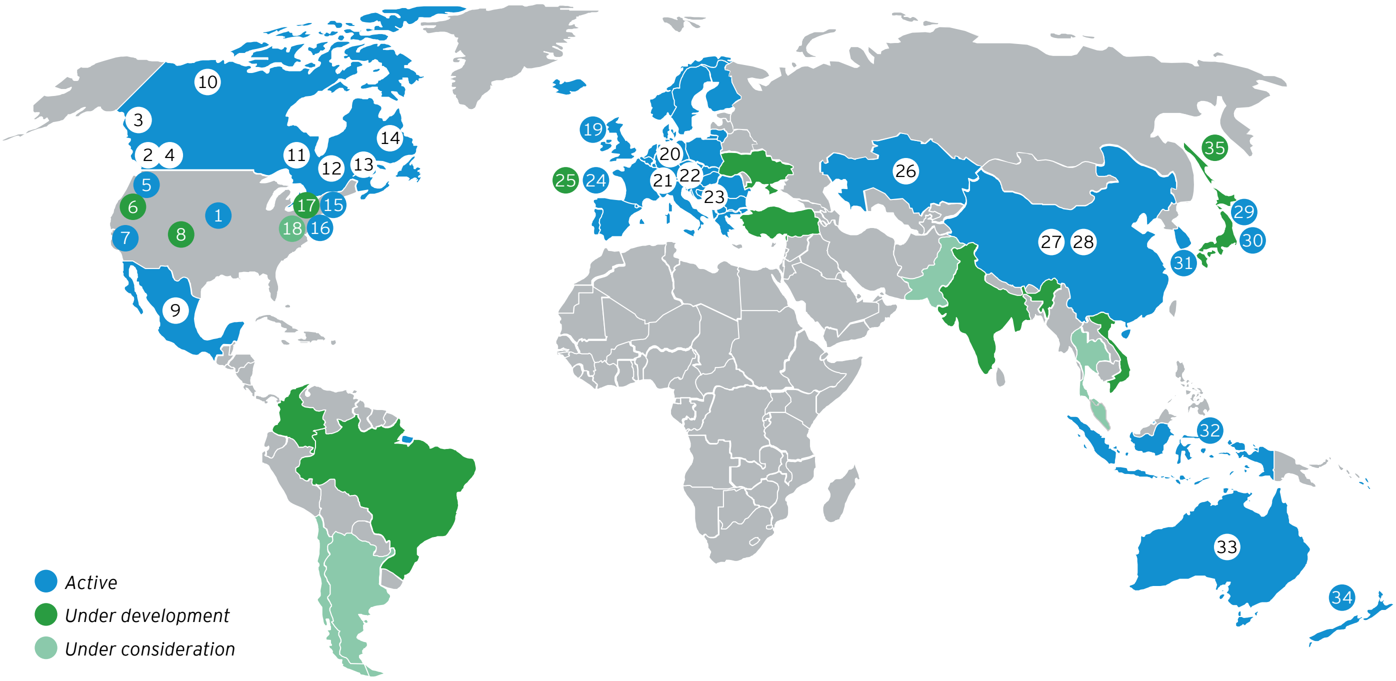


Figure 14

Overview of global ETS systems that have already entered into force or are still under development or consideration

(Source: International Carbon Action Partnership)



- **1 |** Regional Greenhouse initiative: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont
- **2 |** British Columbia Output pricing system
- **3 |** Alberta regulations on technology innovation and emissions reduction
- **4 |** Saskatchewan output-based performance standards program
- **5 |** Washington ETS system
- **6 |** Oregon climate protection program
- **7 |** Californian ETS system
- **8 |** USA – Colorado greenhouse gas emissions and energy management
- **9 |** Mexican ETS system
- **10 |** Canadian federal pricing system
- **11 |** Ontario program for emission performance standards
- **12 |** The Quebec emissions trading system
- **13 |** New Brunswick emissions trading system
- **14 |** Emission standards for Newfoundland and Labrador
- **15 |** Massachusetts limits for emissions from electricity generation
- **16 |** New York
- **17 |** Pennsylvania
- **18 |** Maryland
- **19 |** UK ETS (for aviation, the start is from 2026)
- **20 |** German National ETS
- **21 |** Switzerland ETS
- **22 |** Austrian National ETS
- **23 |** Montenegro ETS
- **24 |** EU ETS
- **25 |** EU emissions trading system for buildings and road transport (“EU ETS 2”)
- **26 |** Kazakhstan ETS
- **27 |** China ETS
- **28 |** China pilots: Beijing, Chongqing, Fujian, Guangdong, Hubei, Shanghai, Shenzhen, Tianjin
- **29 |** Saltana ETS
- **30 |** ETS from Tokio
- **31 |** ETS system of the Republic of Korea
- **32 |** Indonesia’s economic value of the emissions trading system
- **33 |** Australian Safeguard-mechanism
- **34 |** New Zealand ETS
- **35 |** Russian Federation – Sakhalin

- **UK Emissions Trading Scheme:** This cap-and-trade system was introduced in 2021. Companies can trade required or surplus emissions in an auction. Free allowances are also offered for stationary installations, which are set out in the UK ETS Aviation Allocation Table until 2025.[57]
- **USA Regional Greenhouse Gas Initiative (RGGI):** The RGGI program is an emission trading system in which participating power plants and energy suppliers are provided with a certain amount of CO_2 emission allowances. The companies (including airlines) then must reduce their emissions in order to save emission allowances, or they can buy or sell emission allowances on a central market to achieve their objectives.
- Other national ETS systems are shown in Figure 15. Worldwide, 36 ETS systems have come into force, 14 are still under development and eight are currently under consideration.[58]

In the USA, a law was drafted in 2021 that aims to reduce CO_2 emissions from aviation:

- **Sustainable Skies Act:** In May 2021, the US Congress introduced the Sustainable Skies Act to increase incentives for the use of SAF. The participating SAF blenders are granted a subsidy of US$1.50 per gallon, provided they can demonstrate a reduction in CO_2 emissions of at least 50% over the entire life cycle. The subsidy is increased up to a maximum of US$2 per gallon on condition that even higher emission reductions are achieved. The law also stipulates that eligible SAFs must comply with the ICAO's comprehensive sustainability criteria to ensure environmental protection. Another proposal provides for a grant of US$1 billion spread over five years to increase the number of SAF production facilities in the USA. The measures include a planned tax credit for SAF reduce costs and rapidly increase domestic SAF production. In addition, ongoing funding opportunities are being developed to support SAF projects and fuel producers, including the introduction of a new "SAF Grand Challenge" to increase domestic production of SAF.[59]

- **Inflation Reduction Act (IRA):** A comprehensive piece of legislation that addresses various aspects of the US economy, including deficit reduction, energy security, climate change and healthcare. With respect to the aviation sector, the IRA provides tax incentives and grants to encourage domestic production, create well-paying jobs and build more resilient supply chains. One of the significant provisions of the Act is the focus on SAF to reduce emissions in the aviation sector.

Although various regulatory frameworks for CO_2 reduction in aviation have been created, there are still challenges that need to be addressed in order to achieve full integration of the sector into climate policy. The following gaps can be improved in the future:

- Airlines are currently not obliged everywhere to record the emissions of international flights and disclose them in their reports. This leads to a lack of transparent data and makes it difficult to compare companies. Standardizing the recording of emissions and reporting could help to transparency and comparability between companies.

- A common global approach to regulating emissions from the aviation sector does not yet exist and regulations vary between countries. Fully integrating the sector into global climate agreements could take the necessary measures to reduce emissions and achieve climate targets.

- At the international level, it is difficult to reach enforceable international agreements on CO_2 reductions, especially regarding cooperation with countries that pursue other political and economic interests. Forward-looking and sensitive diplomacy is required in this context to agree on appropriate measures for CO_2 reduction and low-carbon aviation.

Advances in technology development and close cooperation between regulators and companies could help to overcome these challenges and create a low-carbon aviation industry.

> "Regulations such as ReFuelEU lack clarity. It remains unclear to what extent airlines have an influence on the supply of SAF under the blending obligation, as suppliers are allowed to decide for themselves when, where and how they fulfill their obligation.
>
> **Henrik von Storch,** Director Global Sustainable Aviation Fuels, DHL Express

SAF demand and offtakers

3

Introduction and summary of the chapter

The demand for SAF is largely determined by regulatory measures. These include both financial incentives and prescribed minimum usage quantities and therefore positively affect the demand for SAF. At the European level, the ReFuelEU initiative, the EU ETS and the RED II and III play a decisive role in demand, as already described.

> Airlines are driven by the risk assessment to secure SAF. This also motivated by potential future penalties. With this in mind, we recently concluded our first offtaker agreement with an airline for the next ten years.
>
> **Dr. Mark Misselhorn,** Chief Executive Officer, Caphenia GmbH

The use of SAF is shaped by both EU and global regulations, as fuel quota obligations incentivize suppliers to fulfill their requirements using the most economically viable fuel options. This can influence the decision to distribute SAF, especially in Germany where greenhouse gas quotas are in place. The EU reforms lead, in the scenario developed by Ernst & Young, to growth in European SAF demand to a total of 73 million tons by 2050, with an average annual growth rate (CAGR) of 11% from 2030 to 2050. A significant increase in the share of SAF in total aircraft fuel demand is also expected to grow internationally due to the individual targets for reducing CO_2 emissions on the part of airlines. Within Europe, the forecasted SAF demand of 73 million tonnes is expected to account to just under 60% of total kerosene consumption.[60]

Non-European government regulations and decarbonisation goals, such as Canada's Aviation Climate Action Plan and India's SAF quota, also contribute to an increase in SAF's global demand. Japan has also set itself the quotas to of replacing 10% of fuel in the aviation sector with SAF starting from 2030.[61] Globally, long-term goals for 2040 and 2050 are not clearly defined in many countries. Primarily, however, they have been established for 2030.

The forecast for 2030 envisages a global SAF supply (according to ongoing projects, projects under construction and projects in the FEED phase) of approximately 15.5 million tonnes[62], which corresponds to a 6% share of global kerosene demand.[63] The current market price for available SAF from biogenic residues is three to five times higher than the price of fossil kerosene.[64] It may continue to change due to high demand and competition. Today, sectors such as aviation compete for SAF-like fuels with other transport sectors such as shipping or the automotive sector (here, E-SAF). However, E-SAF is not yet in high demand due to the expensive CO_2 capture technologies and the dependence on green H_2.

Nevertheless, many airlines conclude purchase agreements to secure the product (mainly bio-based SAF). These supply contracts provide the airlines and producers with security regarding future SAF demand and production. There are also more far-reaching collaborations. Airlines such as Qatar Airways, Delta and United Airlines, for example, founded the First Movers Coalition. This is an alliance of 96 members with the objective of pooling the interests of buyers and supporting producers simultaneously.

The investment that would be necessary to cover SAF demand by 2050 is estimated at a cumulative US$1.00 billion to US$1.45 billion.[65] To enable these investments, producers require a high level of certainty – something that can be ensured through long-term supply agreements

This chapter provides an overview of current and projected SAF demand through 2050. The EY forecast analyses national decarbonization targets – particularly in the aviation sector – and derives corresponding SAF demand projections. It also explores the cross-sectoral competition for SAF and outlines the measures needed to meet future demand.

3.1 Existing and forecasted SAF demand

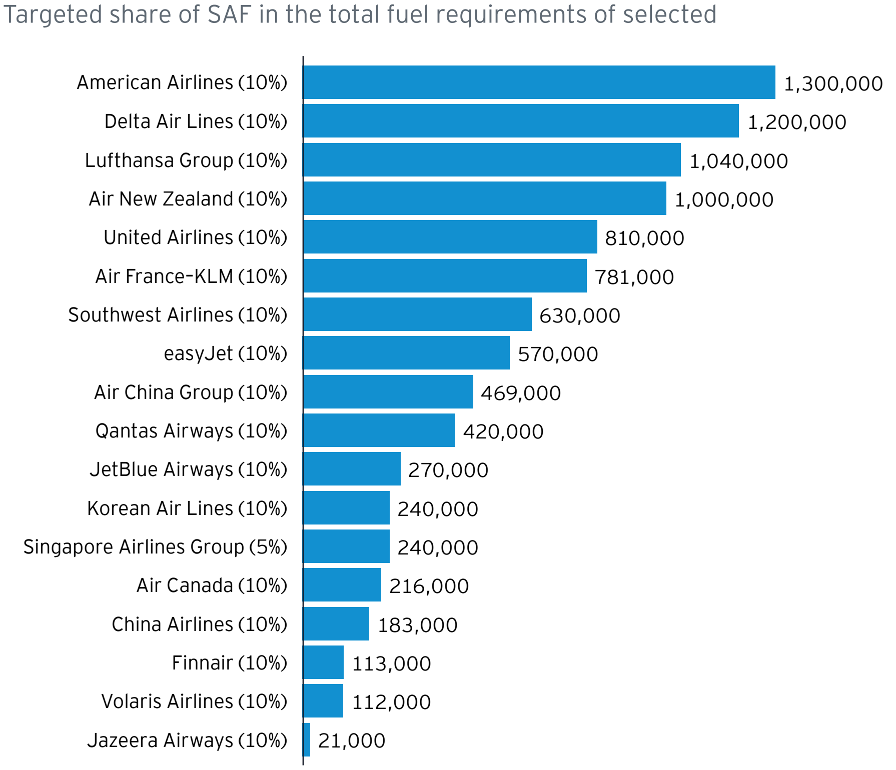
There is currently an increasing demand for SAF. It is driven by political regulations and voluntary commitments by airlines and will continue to rise in the coming years. It is important to meet this future demand to drive the decarbonization of aviation.

At a global level, many major airlines have set ambitious decarbonization targets. A key component of these decarbonization strategies is the increasing use of SAF. Figure 16 shows the targeted SAF shares of selected airlines. For instance, Delta Airlines and American Airlines in North America, Air France-KLM in Europe, and Australia's Qantas Airways plan to meet 10% of their aviation fuel needs with SAF by 2030. Singapore Airlines aims to achieve a 5% share of SAF in Asia and South America within the same timeframe.

Figure 16

Targeted share of SAF in the total fuel requirements of selected

(Source: Airline reports, EY forecasts and interviews as of December 2025)



Drawing on an analysis of existing policy frameworks and national decarbonization targets, Ernst & Young has developed a forecast for global SAF demand by 2050. This model is based on historical global consumption data for kerosene from the U.S. Energy Information Administration (IEA). The forecast of what proportion of this demand will be accounted for by SAF is based on a comprehensive data analysis of national targets worldwide. Where available, these analyzed data are direct regulations that specify the future SAF share of kerosene consumption.

This is the case, for example, for EU member states, where a SAF share of 6% is planned under the ReFuelEU Aviation initiative by 2030. In the long term, the SAF quota in the EU is expected to reach 34% by 2040 and even 70% by 2050. However, globally, most countries do not have such specific regulations. In the absence of concrete decarbonization targets for the aviation sector, this forecast is based on general national decarbonization goals. In these cases, the projected SAF share is based on the assumption that the overall emissions reduction target is transferable to the aviation sector. The forecasting model takes into account that, in addition to the use of SAF, there are other measures to reduce aviation emissions. Current research suggests that, for example, optimizing flight routes could save around 20% in emissions.[66]

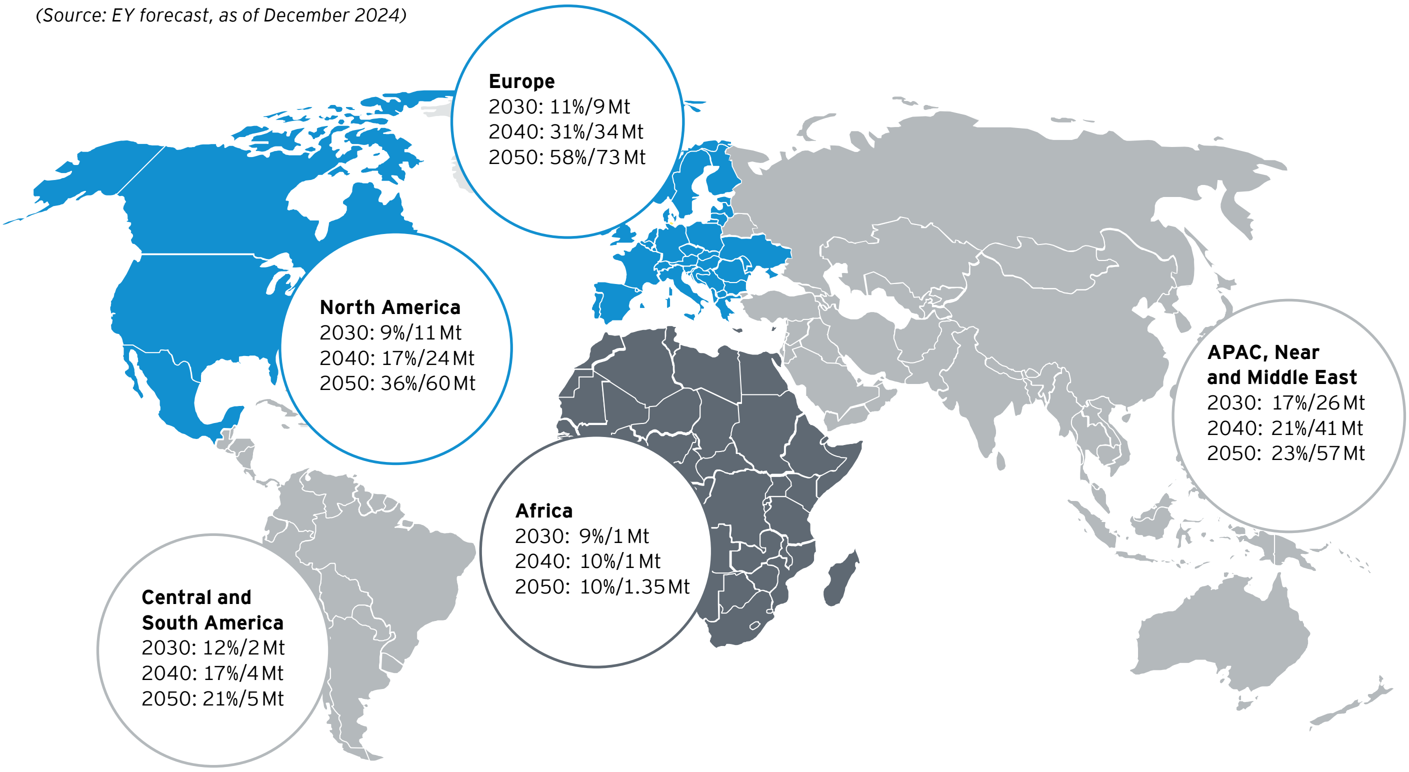
It should also be noted that the assumptions made in the forecast are subject to high uncertainties due to the long forecasting period. These assumptions could be significantly influenced by future changes in SAF production costs, efficiency, and regulatory frameworks. Therefore, changes may occur in the course of SAF projects compared to with the projected scenario.

The results of the forecast for global SAF demand by 2050 are visualized in Figure 17. A strong increase in absolute SAF demand is expected, with a global average annual growth rate of 7% between 2030 and 2050. This corresponds to an increase in global demand from 49 million tonnes in 2030 to 104 million tonnes in 2040, reaching up to 196 million tonnes by 2050.

Figure 17

Forecasted SAF demand by region (in %) of total kerosene demand and absolute SAF volumes

(Source: EY forecast, as of December 2024)

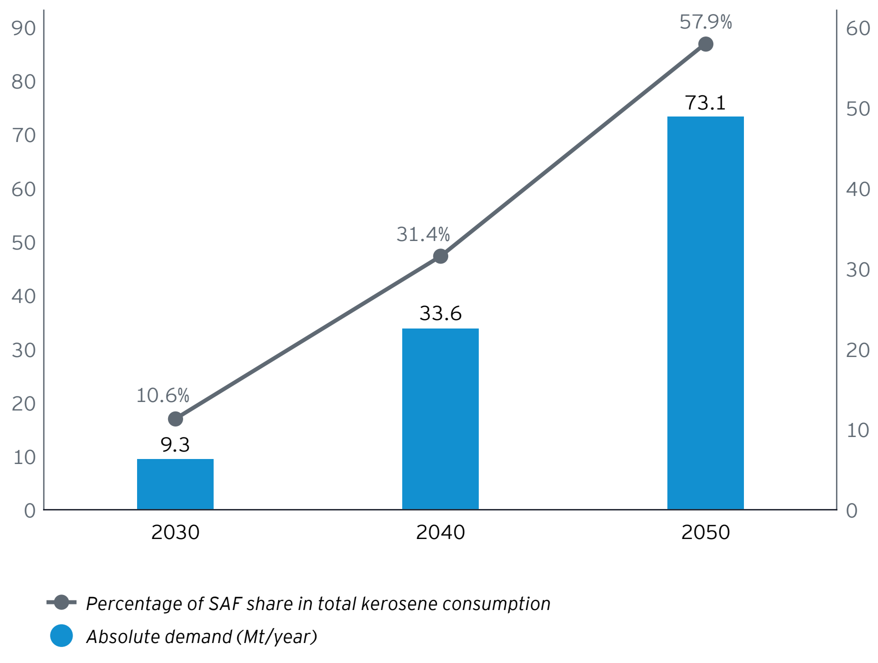


For the **European region**[h], a near-exponential trend can be observed in this forecast scenario, as shown in Figure 18: While the SAF share of kerosene consumption was still 0.2% in 2023, a share of 10.6% is already expected for 2030, corresponding to a total volume of 9.3 million tonnes of SAF. Meanwhile, the SAF share of 31.4% is forecasted for 2040. By the middle of the century, more than half of Europe's kerosene demand could be covered by SAF, which corresponds to a total demand of 73.1 million tonnes. This development reflects an average annual growth rate of 11% between 2030 and 2050 and, thus, the strongest increase in SAF demand compared with other regions.

Figure 18

Projected development of SAF demand in Europe

(Source: EY forecast, as of December 2024)



h In addition to the EU, Europe includes the UK, Norway and Turkey, which have formulated national SAF targets.

The forecasted absolute demand of 73 million tonnes by 2050 in Europe would correspond to the largest consumption compared with other regions, followed by North America, with an expected absolute demand of 60 million tonnes of SAF in 2050.

The second largest increase in demand for SAF is expected in North America, with a forecasted average annual growth rate of under 9%. Significantly lower but still relevant growth in SAF demand can be forecast in other regions.

Annual growth of around 4% is expected in Central and South America, as well as in the Asia-Pacific (APAC) region and the East between 2030 and 2050. The African continent brings up the rear with an average annual growth rate of just under 2%. The lowest consumption is expected there, with demand for SAF projected to increase from 8.5% in 2030 to 10.3% in 2050. This corresponds to a total demand of 0.95 million tonnes (2030) or 1.35 million tonnes (2050).

The growth rates described above result in a forecast absolute demand of 26 million tonnes in 2030, 41 million tonnes in 2040 and 57 million tonnes in 2050 in the APAC region and the Middle East. Despite similar growth rates, the absolute demand in Central and South America will be significantly lower at 2 million, 3.7 million and 5 million tonnes, respectively, in the same period.

3.2 Important sectors as key customers

In the first chapter, we explained the various process routes for producing SAF. These refinery processes yield not only SAF but also other sustainable fuels as by-products. These additional fuels can power other transportation modes, such as trucks and ships. The chemical sector and other industries may also find these by-products valuable for their operations. The quantity ratio of the various end products to each other can be adjusted in production.[67] Given the global objective of reducing CO_2 emissions in the entire transport sector, there could be competition between aviation and other transportation modes, such as shipping, for the provision of SAF (especially E-SAF) in the short to medium-term.

In recent years, biomass refining processes have primarily targeted the production of diesel and gasoline for road transport. Only recently have bio-based SAF and marine diesel gained greater attention in the industry. The reasons for this shift include relatively high prices and limited production capacities. To drive decarbonization in aviation, manufactures would need to adjust the quantity ratios of end products to prioritize bio-based SAF production.[68]

E-SAF is not currently in high demand, as the technology for CO_2 capture is relatively expensive, and production is heavily dependent on the availability of green H_2. However, just as in the production of biofuels, various fuel types can be produced in the same process route, and these can also be used by multiple types of transportation. According to recent studies, a favorable distribution of quantities that promotes the decarbonization of

aviation would involve the production of 50% E-SAF, 25% E-Diesel and 25% E-Naphtha (raw gasoline, which serves as a base product to produce aviation fuel, among other uses).

The assessment of this distribution is based on technical, production-related aspects and on consideration of alternative options for CO_2 reduction and corresponding efficiency aspects.[69]

In the EU, for example, the RED III Directive now also regulates the use of marine diesel and aviation fuel, in contrast to RED II. The final effects of these regulations on the production and use of SAF in competition with other end products depend on demand and the achievable price in various application areas. Various sustainable fuel types can be counted towards fulfilling the quota obligations in the RED III Directive. In addition to Bio-SAF, this has also included E-SAF in Germany since April 2024, which was produced using renewable energy.[44] SAF and other fuels, therefore, compete with each other. Distributors will likely make decisions regarding quantity ratios in a way that allows them to meet their own quotas in the most cost-effective manner.

In Germany, due to the GHG quota, the fuel that is primarily distributed is the one that is most cost-effective for consumers. However, in other EU countries, this could differ depending on the specific national implementation of the Directive.[69] Other factors such as national demand for the individual types of renewable fuels and the degree of direct electrification of transport also influence the ratio of SAF production to other fuels.[70]

Despite the potential to increase e-fuel production in the future, bio-based SAF availability is a key factor in meeting future demand. To give bio-based SAF an advantage over other sustainable fuels, further guidelines or political incentives could be appropriate policy tools. It should also be noted that the use of bio-based SAF is still limited to a maximum ratio of 50% of bio-based SAF to conventional.[71]

Based on technical factors, the availability of raw materials, production costs and the effects on the decarbonization of the entire transport sector, it is possible to analyze which types of fuel should be prioritized under different process routes to achieve the most advantageous result. Figure 19 provides an overview of a possible prioritization. However, it should be noted that all the fuel types listed require further development and scaling to contribute to the necessary decarbonization in an economical way.

Figure 19
Prioritization of different fuels for use in the transport sector[72]

		Means of transportation							
		Aviation		Shipping		Road transport (passengers)		Road transport (heavy goods)	
Fuel type		Short distance	Long distance	Short distance	Long distance	Short distance	Long distance	Short distance	Long distance
Biofuels	e.g., FT-SPK-SAF and liquefied gases	Highly prioritized	Highly prioritized	Good suitability	Highly prioritized	Limited suitability	Limited suitability	Limited suitability	Limited suitability
	e.g., ATJ-SPK SAF and biodiesel	Highly prioritized	Highly prioritized	Good suitability	Highly prioritized	Limited suitability	Limited suitability	Limited suitability	Limited suitability
	e.g. HEFA SAF and HVO-diesel	No prioritization	Limited suitability	No prioritization	Limited suitability	No prioritization	No prioritization	No prioritization	No prioritization
E-fuels	e.g., PtL SAF and e-gasoline	Highly prioritized	Highly prioritized	Good suitability	Highly prioritized	No prioritization	Limited suitability	Limited suitability	Average suitability

> Once large-scale production of E-SAF operates efficiently, it is expected that the demand for biofuels will decrease.
>
> **Jan Eike Blohme-Hardegen,** Head of the Environmental Department, Hamburg Airport

To decarbonize the transport sector, increasing energy efficiency, electrification and the use of H_2 and its derivatives are crucial. Direct electrification from renewable and other low-carbon resources is considered the best option for decarbonizing road transport and is also suitable for inland shipping and short-sea shipping. However, supply chain bottlenecks and geopolitical issues related to critical materials pose a challenge to this approach.

Biofuels, especially drop-in biofuels, are highly compatible with existing fossil fuels up to the respective blending limit and have a competitive cost profile, especially in the short term. However, their availability is limited if the focus is on sustainable raw materials. In addition to the already limited availability, there is also a competing demand for biogenic carbon from other sectors, such as construction and the chemical industry. Due to this scarcity, the use of biofuels should prioritize those modes of transport where decarbonization by other means is difficult. This mainly includes aviation and shipping.

E-fuels face challenges, particularly regarding costs, technological readiness and energy efficiency. This limits their potential contribution to the decarbonization of the transport sector in the short term. However, it is expected that E-SAF will play a relevant role in the long term.

In summary, a combination of different fuels will be necessary for a successful decarbonization of the transport sector, particularly aviation. This is based on the varying technical and economic feasibility of production processes for different modes of transport and the need to balance costs, energy, resource availability and efficiency.

The development of new infrastructure and technical standards, as well as further research and demonstration initiatives, is crucial to support the transition to sustainable fuels and achieve net zero in the transport sector by 2050.[72]

According to a study[72], spending on renewable fuels to achieve the EU's net-zero target should be prioritized as follows: By 2030, it is expected that a large portion of total investments will still flow into fossil fuels. Nevertheless, it is anticipated that investments in biofuels, including Bio-SAF, will reach a level of approximately US$40 billion. Investments in H_2 and other sustainable energy-based fuels (such as E-SAF) are not expected to reach a significant scale at that time. This picture must change significantly by 2050 to achieve net zero. We predict that investments in fossil fuels will cease, while investments in H_2 and other sustainable energy-based fuels are expected to rise to approximately US$150 billion. Investments in biofuels are likely to increase to US$60 billion during this period.

In addition to aviation, shipping is also a sector that tends to be difficult to decarbonize. Direct electrification is unsuitable here due to the limitations of electricity storage. In 2019, around 46 million tonnes of marine fuel were consumed within the EU. In order to meet the objectives of the FuelEU Maritime Regulation, this consumption results in a future demand for SAF-like renewable fuels for the shipping sector of around 1 million tonnes in 2034.[72]

In contrast to the SAF used in aviation, there is no need for certification of the fuel used from the same process routes in shipping. For this reason, e-ammonia can also be used in addition to e-methanol.[73] However, the ship's engines must be designed for this, including by means of dual fuel engines, which can be operated with both (biogenic) marine diesel and additionally with methanol, for example.[74] In addition to H_2, e-ammonia will play a central role in transforming the shipping sector. This transformation is necessary to achieve the objective of reducing CO_2 emissions by 50% by 2050, as defined by the International Maritime Organization. In the short term, LNG and biofuels are expected play an important role in reducing the use of fuel oil and marine gasoil (MGO).

Road transport also competes with aviation for the provision of sustainable fuels, as the same production pathways can be used not only for the production of SAF but also for bio or e-gasoline. However, considering the entire transport sector, prioritizing SAF over fuels for cars and trucks would be desirable for successful decarbonization. This is because direct electrification is technically and economically feasible in the automotive sector.

The choice of the appropriate fuel for the respective means of transportation, depends to a large extent on factors such as supply, engine technology, net environmental performance and economic viability. The decisive factors are likely to be production costs and availability. In addition, logistical, infrastructural and safety aspects must be taken into account when choosing an alternative fuel.[75]

> “To secure the required SAF volumes, we require long-term contracts. We are currently negotiating contracts with a term of eight to 12 years. We have also invested in innovative projects in the USA and the Netherlands to support research and drive the development of new technologies. E-fuel projects are also a focus of our support; eleven projects are currently under development in France, for example. We are in active discussions with some of them to strengthen their business foundations.
>
> **Air France-KLM Group**

3.3 Securing the product – overview of existing cooperations

Increasing the demand for SAF is associated with numerous difficulties, partly due to the current high price premium over fossil kerosene. This is because it often does not make sense for airlines to focus financial resources on SAF from a competitive perspective due to the current price discrepancy between SAF and conventional kerosene. The First Movers Coalition was founded during COP26 and COP27 to address these challenges in an appropriate manner. The objective of this alliance is to bundle the interests of the buyers of decarbonization technologies and to create additional security for the producers by issuing commitments from the members. These decarbonization technologies also include the development of SAF. The First Movers Coalition currently has 96 members, including from the aviation industry.[76, 77]

To secure production, many airlines are looking to conclude long-term supply contracts with current and potential future producers of SAF, among other things. These supply contracts provide airlines with security in terms of being able to meet their future projected SAF demand, and they also offer producers assurance that the SAF quantities they produce will be purchased. However, in the majority of the currently concluded supply contracts, they are merely memoranda of understanding (MOUs), which are only statements of intent regarding the future purchase of SAF and are therefore not legally binding.

Nevertheless, these agreements can serve to expand partnerships between SAF producers and buyers, underline their own sustainability goals and increase security for producers. Possible further types of cooperation arise through the equity participation of airlines in start-ups in the SAF sector, whereby these cooperations are mainly aimed at supporting technological research.

High investments in production facilities are required to cover the enormous forecasted increase in demand for SAF. To ensure the required increase in the number of production facilities by 5,000 to 7,000 units by 2050, a cumulative investment requirement of US$1 trillion to US$1.5 trillion would be required. This corresponds to an annual global investment requirement of 6% to 10% of the current annual oil and gas infrastructure investment. From the airlines' point of view, this requirement should mainly be covered by the oil industry. The investments in future production facilities can also be secured through the conclusion of supply contracts.[67]

Globally, many airlines and airports are cooperating with companies such as Shell to drive the expansion of SAF production capacities. Examples of cooperation include United Airlines, which partners with two other companies specializing in technology and infrastructure development for sustainable energy sources. The Blue Blade Energy is a joint venture that should enable the airline to operate 50,000 flights using SAF in 2028.[78] United Airlines also concluded a supply contract for the future delivery of 4.5 million tonnes of SAF with the start-up Alder Rene-wables (Table 7).[79] Delta Air Lines has also concluded a similar partnership in North America with DG Fuels, a company that plans to invest US$3.8 billion in a production plant for the manufacture of SAF using FTS.[80, 81]

Figure 20 shows the off-take agreements concluded worldwide from 2013 to 2024.

Table 7

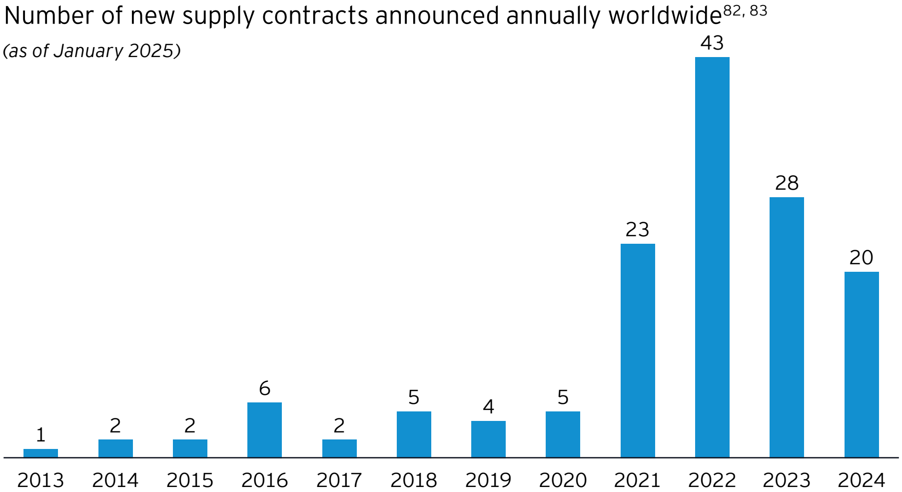
Examples of global supply contracts with the highest volumes in recent years *(as of January 2025)*

Name	Date	Producer	SAF volume (million tonnes)	Contract duration (in years)
United Airlines	30.06.2015	Fulcrum	3.4	10
AirBP	01.11.2016	Fulcrum	1.5	10
United Airlines	09.09.2021	Alder Renewables	4.5	20
Oneworld	20.03.2022	Gevo	3.0	5
Delta	22.03.2022	Gevo	1.6	7
American Airlines	22.07.2022	Gevo	1.5	5
United Airlines	13.09.2023	Cemvita	3.0	20
Southwest Airlines	03.11.2023	USA BioEnergy	2.6	20
Shell	January 2025	ECB/Omega Green	0.8	n.a.

Figure 20

Number of new supply contracts announced annually worldwide[82, 83]

(as of January 2025)



In Germany, Lufthansa has a partnered with the established German chemical company HCS Group, which will produce 60,000 tonnes of SAF per year from 2026. The SAF will be produced from the AtJ route, based on biological residues from agriculture and forestry. Lufthansa plans to invest up to an additional US$250 million in the procurement of SAF in the coming years.[84, 85]

Below is an overview (Table 8) of other existing SAF supply contracts in Germany.

Tabelle 8
Overview of the major supply contracts of German companies
(as of January 2025)

Name	Date	Producer	SAF volume (million tonnes)	Contract duration (in years)
Lufthansa	07.08.2016	Gevo	121.1	5
Lufthansa Cargo	04.10.2021	Atmosfair	0.0001	5
DHL Express	21.03.2022	Neste	0.6	5
Lufthansa	01.08.2022	Shell	1.8	7
Lufthansa	13.09.2022	OMV	0.8	8
Lufthansa	01.08.2023	HCS Group	0.06	1
DHL Express	19.10.2023	World Energy	0.5	7

The above-mentioned cooperations and supply contracts currently only cover bio-based SAF. For E-SAF, the number of supply contracts is much more limited due to the current technological uncertainty and lack of commercialization of the technology. Nevertheless, there are also isolated efforts in this area. One example in Europe is the company Norsk e-Fuel, which has concluded corresponding agreements regarding E-SAF with the airlines Norwegian Air Shuttle and Cargolux. Norsk e-Fuel is a start-up whose shareholders include the German manufacturer of electrolysis systems Sunfire and the Swiss provider of CO_2 capture technologies Climeworks.[86, 87]

When concluding supply contracts, several critical parameters must be considered. For example, in addition to other terms and conditions, supply contracts should contain information on the producers and customers, the airport to be used, the production volume and the necessary time horizon. To avoid risks arising from price fluctuations, airlines should carry out appropriate hedging transactions on the global financial markets.

As already described, the refueling options at airports play a central role in successfully using SAF and implementing supply contracts. If airlines do not have access to the necessary infrastructure at the airports relevant to them (see Chapter 5), this affects their ability to use SAF. In these cases, it is still possible to enter into supply contracts with producers via so-called book-and-claim systems, even without physically refueling the SAF. Affected airlines can enter contracts with SAF producers and pay them the price difference between SAF and fossil kerosene. This enables the respective airline to offset the SAF paid against its own CO_2 balance. The respective quantity of SAF is then physically sold elsewhere at the market price of fossil kerosene and refueled by a customer on whose CO_2 balance the SAF has no positive influence. In addition, this system allows airlines and other companies that do not operate their own flights to benefit from CO_2 savings through SAF. One example of such supply contracts is provided by the producer Neste, which allows companies to pay the corresponding green premium between SAF and conventional kerosene and have the resulting emission reductions credited to their CO_2 balance. The SAFs subsidized by third parties in this way are then sold to other airlines as final customers.[88]

Global production capacity

4

> We assume that the production of E-SAF will not be economically viable before 2030 and is only likely to gain in importance after this time. Until then, the aviation industry is likely to be dependent on the production of Bio-SAF.

Jan Eike Blohme-Hardegen, Head of the Environmental Department, Hamburg Airport

Introduction and summary of the chapter

According to IATA data, the global production of SAF has seen exponential growth in recent years. From 2019 to 2022, the production volume increased from 0.02 million tonnes to 0.24 million tonnes.[89] IATA assumes that SAF production will reach 2.1 million tonnes or 0.7% of total jet fuel production in 2025.[90]

Multiple production pathways are currently in use, with HEFA/HVO remaining the dominant technology. However, FT and ATJ processes also demonstrate strong potential for scalable SAF. In contrast, the deployment of e-SAF remains limited compared to bio-based SAF, primarily due to the high cost of key inputs such as renewable electricity, green hydrogen, and CO, along with the associated technological requirements.

Although more than 264 projects have already been announced, SAF's current production level remains comparatively low, as the implementation status of such projects is relatively unclear. Most of them are planned in North America, followed by Europe and Asia. There are currently 39 production facilities worldwide, including nine demonstration plants. Two of these active plants are located in Germany: a Bio-SAF, which produces the fuel using co-processing, and an E-SAF, which produces it using PtL technology.[91]

A differentiated analysis of the SAF potential by type shows different growth prospects. E-SAF could grow strongly due to falling costs for H_2, electrolysis and DAC technologies, especially in areas with low biomass reserves. This growth is expected to outpace that of other sustainable fuels, especially if renewable energy sources such as wind and solar power are available.

Expanding the availability of green H_2 is crucial to meet the increasing demand for SAF and to achieve the objectives of decarbonizing the aviation industry. This requires not only an increase in production overall, but also a transition from gray to green H_2 produced from sustainable electricity sources.

Stronger growth is expected for bio-based SAF from 2030 to 2035, both globally and in Europe and Germany. The share of the announced annual production of SAF "made in Germany" is expected to account for 1.5 million tonnes by 2030. This corresponds to an average plant size of 75,000 tonnes per year in Germany in 2030.

The following chapter provides an overview of the current and future possibilities for SAF production. These are differentiated by region in parallel to the demand forecast in Chapter 3. Finally, demand and production potential are put in relation to each other and emerging production gaps are analyzed.

4.1 Global production potential

A global increase in SAF production is forecast for the coming years. According to the ICAO, more than 150 producers in 53 countries have announced over 264 projects for renewable fuels, which are expected to reach a total capacity of 65.4 million tonnes of renewable fuels.[64]

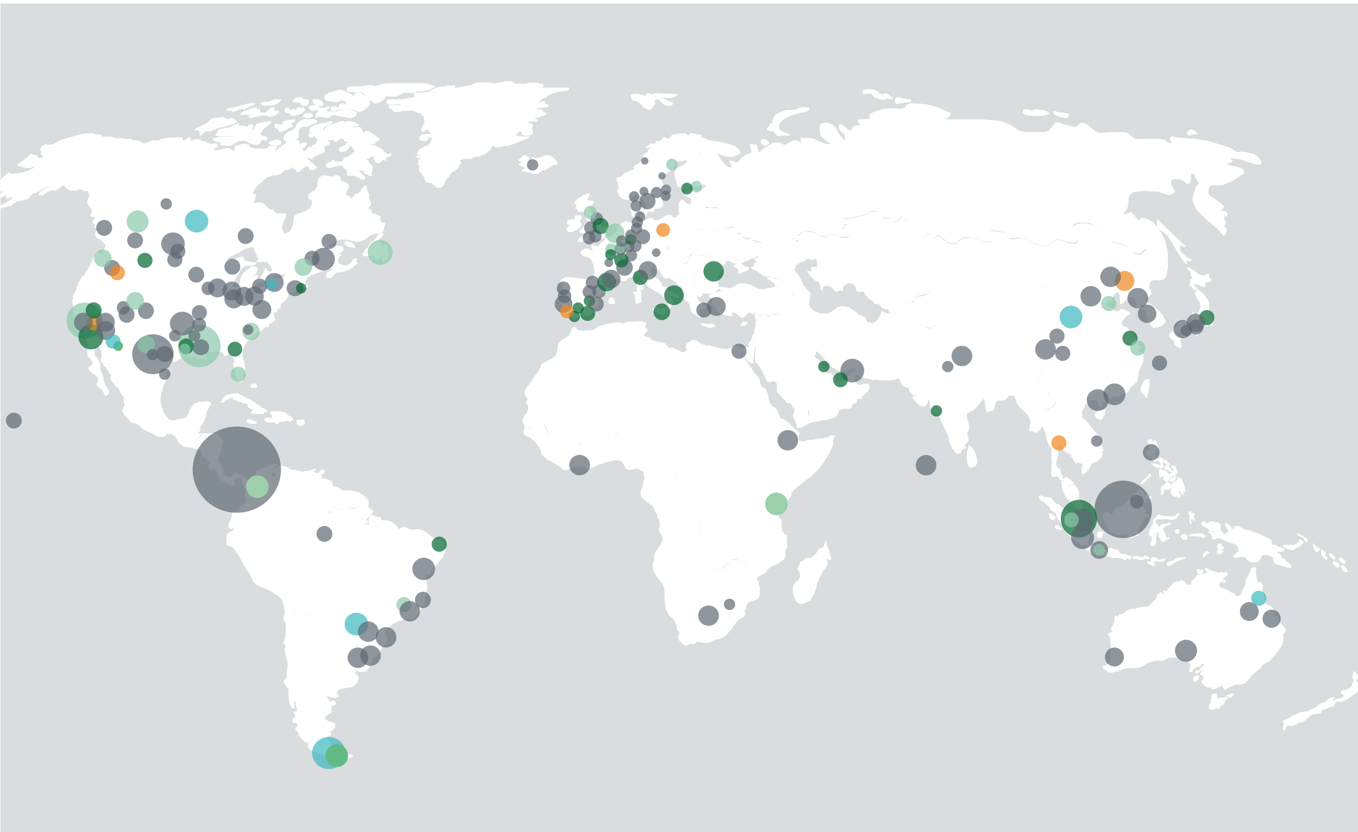
Figure 21 below shows the geographical distribution of existing and planned production sites potentially capable of producing SAF. However, it should be noted that neither the successful completion of these projects nor the actual extent of SAF production can be reliably predicted. The figures given below are, therefore, potential maximum quantities. Most of the outstanding projects (234 plants) have only been announced so far, with a smaller number already in the construction phase (12 plants) or the front-end engineering design (FEED) phase (18 plants). For some of these plants that have not yet started production, no announcements have yet been made regarding the expected production volume.

Accordingly, these are excluded from the production volumes presented in the following sections. Thirty-nine production plants for SAF are already in operation worldwide. Most of the planned facilities are located in North America: 72 plants in the USA and 28 in Canada. In Europe, 76 plants are in the planning phase. In addition, several plants can be seen in East and South East Asia, in particular (especially in Japan, Malaysia and China), and in South America (especially in Brazil). In contrast, only 11 plants are planned for the African continent. Most of the announcements were published in 2024.[64]

Figure 21

Overview of production facilities for sustainable fuel in planning[64]

(as of January 2025)



Capacity (ML/Year)

0.0 K ● ● ● *9.8 K*

Plant status

- *Announced initiatives*
- *Under construction*
- *In operation – Production of renewable fuels*
- *In operation – SAF production*
- *FEED status*

By 2030, volumes could increase by 14 million tonnes of SAF in North America, by 9.5 million tonnes in Europe and by 9.9 million tonnes in the APAC region and the Middle East.[64] Overall, a significant number of new SAF projects are expected to be launched, accompanied by a growing geographical diversification of production sites. In particular, projects are being developed in North and South America, Australia, Europe, Saudi Arabia and South Asia. More projects are generally expected in North America, Europe and Asia. Since SAF production only accounts for a portion of the potential output in these facilities, it is, as described in Chapter 3.2, in a competitive relationship with renewable diesel or naphtha production, for example.[92]

Table 9 shows selected production plants with high production volumes for bio-based SAF worldwide. It is noticeable that these plants are particularly specialized in the HEFA process route and are mainly located in Europe, Asia and North America.

Table 9

Selected production plants with a high potential production volume for bio-based SAF (active, under construction, announced)[64]

The company	Country	Maximum SAF volume	Completion	Processes	Status
TotalEnergies	France	0.5 million tonnes/year	2019	HEFA	Active
ENI	Italy	0.5 million tonnes/year	2021	HEFA	Active
ECB Omega Green	Paraguay	0.9 million tonnes/year	2022	HEFA	FEED
Neste	Singapore	2.7 million tonnes/year	2023	HEFA	Active
TotalEnergies	France	0.08 million tonnes/year	2024	HEFA	Active
Grön Fuels	USA	3.0 million tonnes/year	2025	FT-SPK	Announcement
Cepsa	Spain	0.5 million tonnes/year	2026	HEFA	Under construction
SGP BioEnergy	Panama	7.9 million tonnes/year	2026	Not specified	Announcement
Azure	Canada	0.9 million tonnes/year	2027	HEFA	FEED
World Energy	USA	0.93 million tonnes/year	Ongoing	HEFA	Active
Sarawak State	Malaysia	4.6 million tonnes/year	2030	Not specified (algae)	Announcement

> We use an advanced process to produce SAF and sustainable fuels based on biomethane and CO_2. The major advantage of this process is the lower energy consumption. With the Caphenia method, we can achieve a CO_2 reduction of up to 92%. We also obtain H_2 very cost-effectively, as it is produced with significantly less energy than water electrolysis.
>
> **Dr. Mark Misselhorn,** Chief Executive Officer, Caphenia GmbH

H_2 plays a central role in the production of E-SAF. However, the product must be "green," meaning it is produced from renewable energy sources. Currently, alongside technological limitations, the restricted availability of the green H_2 is a reason for the low production volume of E-SAF. However, due to potentially decreasing costs of green H_2 and direct air capture (DAC) technologies, the World Economic Forum (WEF) assesses the potential of CO_2-based E-SAF as high. It is expected that the production of E-SAF will grow faster in the coming decade than the production of other sustainable fuels. Power-to-Liquid (PtL) is intended to contribute to the diversification of SAF production, particularly in areas with limited biomass reserves. To produce E-SAF, it is imperative that renewable energy sources, primarily wind and solar energy, are available. Particularly sparsely populated, non-agricultural areas, such as in Chile, the Middle East, North Africa, or Australia, would be optimal locations for E-SAF production.

According to the WEF, production in sunny locations is attractive due to its cost-efficiency. In desert areas, for example, the production of E-SAF could be 25% cheaper than in Europe. The use of just 1% to 2% of the land area in, for example, four desert regions could cover the entire demand for aircraft fuel for the year 2030.[93]

According to Agora, the planned commissioning of numerous facilities from 2026 onwards could result in an annual production of approximately 137,000 tonnes of E-SAF. A key driver of this development is the conversion of existing FT facilities to produce CO_2-based SAF. Table 10 provides an outlook on two existing and other planned E-SAF projects that are scheduled to operate by 2027.[75]

In contrast to E-SAF, our forecasts for bio-based SAF show stronger global growth by 2030, which could reach almost 34.7 million tonnes at full plant capacity utilization. Similar expectations also apply to Europe, where an increase to 6.7 million tonnes can be expected by 2030.[64]

Table 10

Selected existing and announced E-SAF projects with their respective potential production volumes[64]

The company	Country	Maximum SAF volume	Completion	Processes	Status
Atmosfair	Germany	0.0004 million tonnes/year	2022	Power-to-Liquid	active
AirCompany	USA	0.6797 million tonnes/year[94]	2022	Power-to-Liquid	active
Synerko	Netherlands	0.1000 million tonnes/year	2027	Power-to-Liquid	announced
SAF+ Consortium	Canada	0.0800 million tonnes/year	2028	Power-to-Liquid	announced
Twelve	USA	0.0002 million tonnes/year	2025	Power-to-Liquid	Construction phase

E-SAF-Project

4.2 Global production potentials

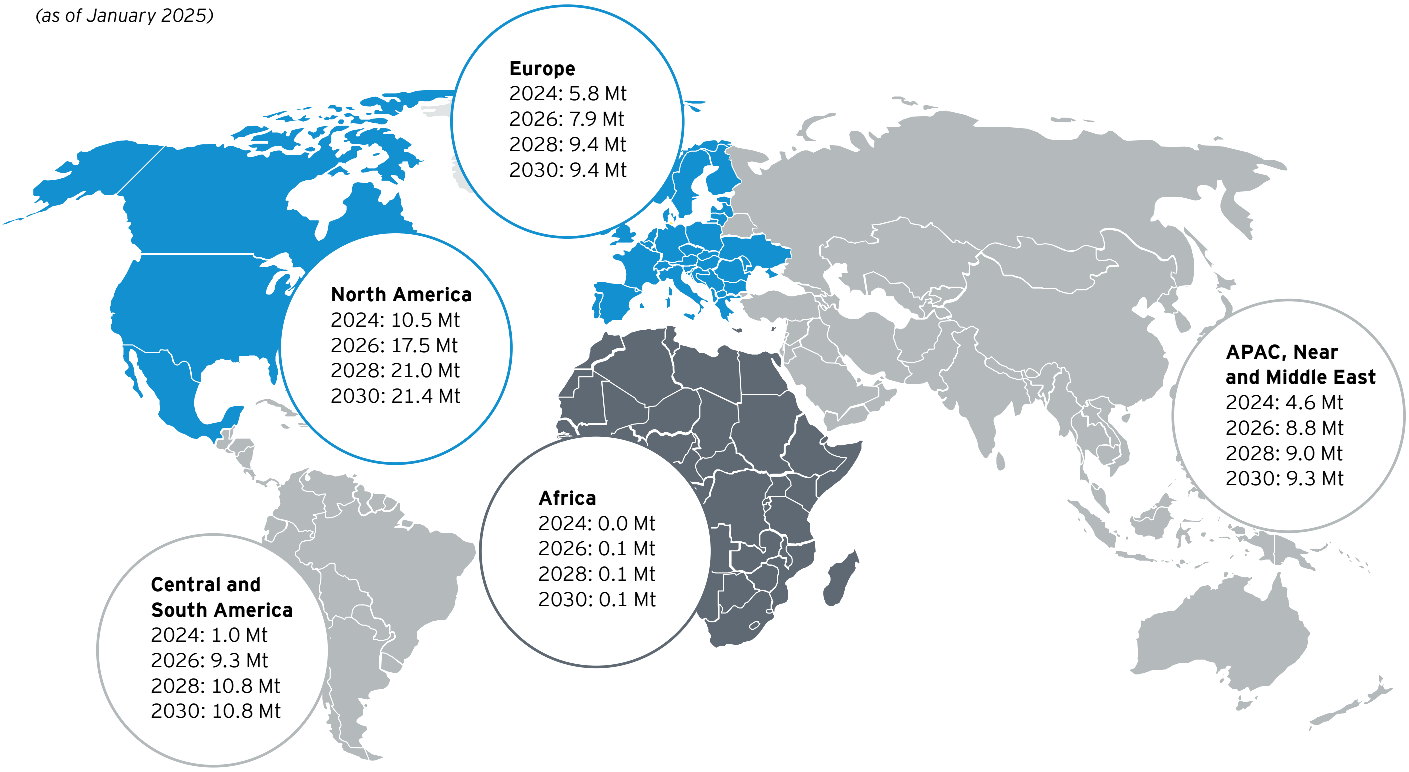
Although there is a noticeable global trend towards increasing SAF production volumes, there are regional differences in the speed and scale of this ramp-up. These differences are summarized in the map below (Figure 22).

> Regions with abundant resources to produce green H_2 are becoming increasingly important for SAF production. This can already be clearly seen in the locations of current projects.
>
> **Melanie Form,** Member of the Management Board and Managing Director, Aireg

Figure 22

Maximum SAF production potential in existing or announced plants by 2030[64]

(as of January 2025)



It is noticeable that the largest production volume is expected in North America, particularly in the USA. In a global comparison, the predicted production capacities in Africa and Central and South America are very low. In the remaining regions, potential SAF production by 2030 is projected to be of a similar magnitude, at approximately 10 million tonnes. However, differences can be seen in the growth rate and the speed of production expansion.

The map shows the maximum production potential, which depends heavily on political decisions and governments. It remains unclear to what extent, for example, different feedstocks that are relevant for bio- or E-SAF will be prioritized.

Figure 23 illustrates the number of SAF projects planned or already in operation by 2050. The number of active plants is currently equally dominated by Europe, North America and Asia. Clearly, Europe and North America have the greatest potential for the construction or expansion of plants, while Asia has a lower presence in terms of growth.[64] A similar picture also emerges when considering the forecast potential production volumes up to 2030.

In a direct comparison of individual countries, the USA shows a clear dominance in the number of both existing and planned SAF production facilities. As shown in Figure 25, the country currently hosts seven operational facilities and an additional 93 planned sites, making it by far the global leader in terms of SAF production locations. This number accounts for approximately one-third of the globally existing and planned SAF production facilities. In second place – though by a considerable margin – is the United Kingdom, with a total of 34 existing or planned facilities.

Figure 23

Number and degree of implementation of SAF projects by continent[64]

(as of January 2025)

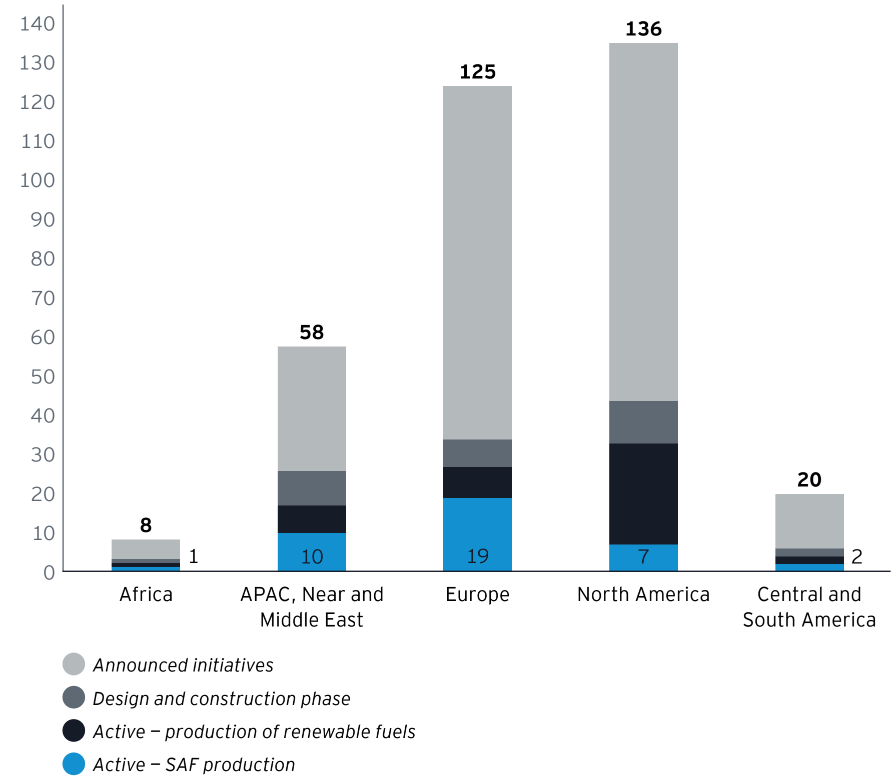
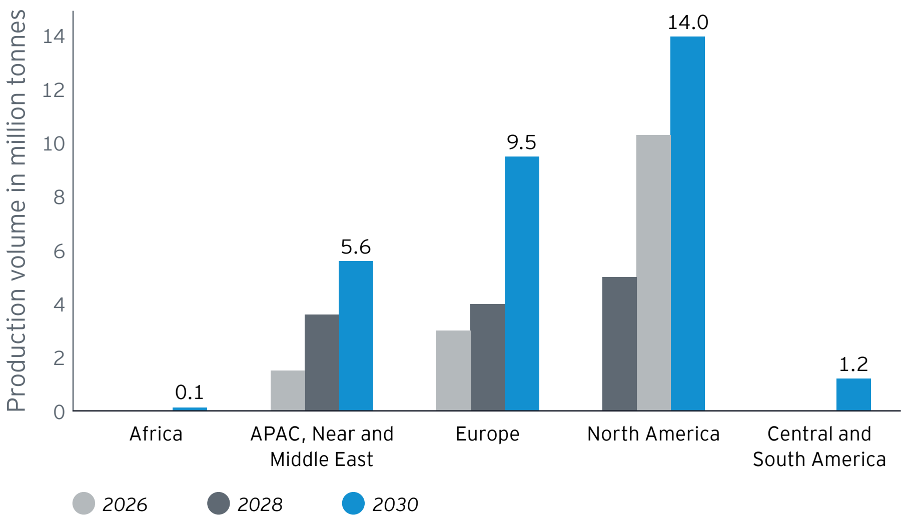


Figure 24

Announced potential SAF production volumes by continent (2026-30)[64]

(as of January 2025)



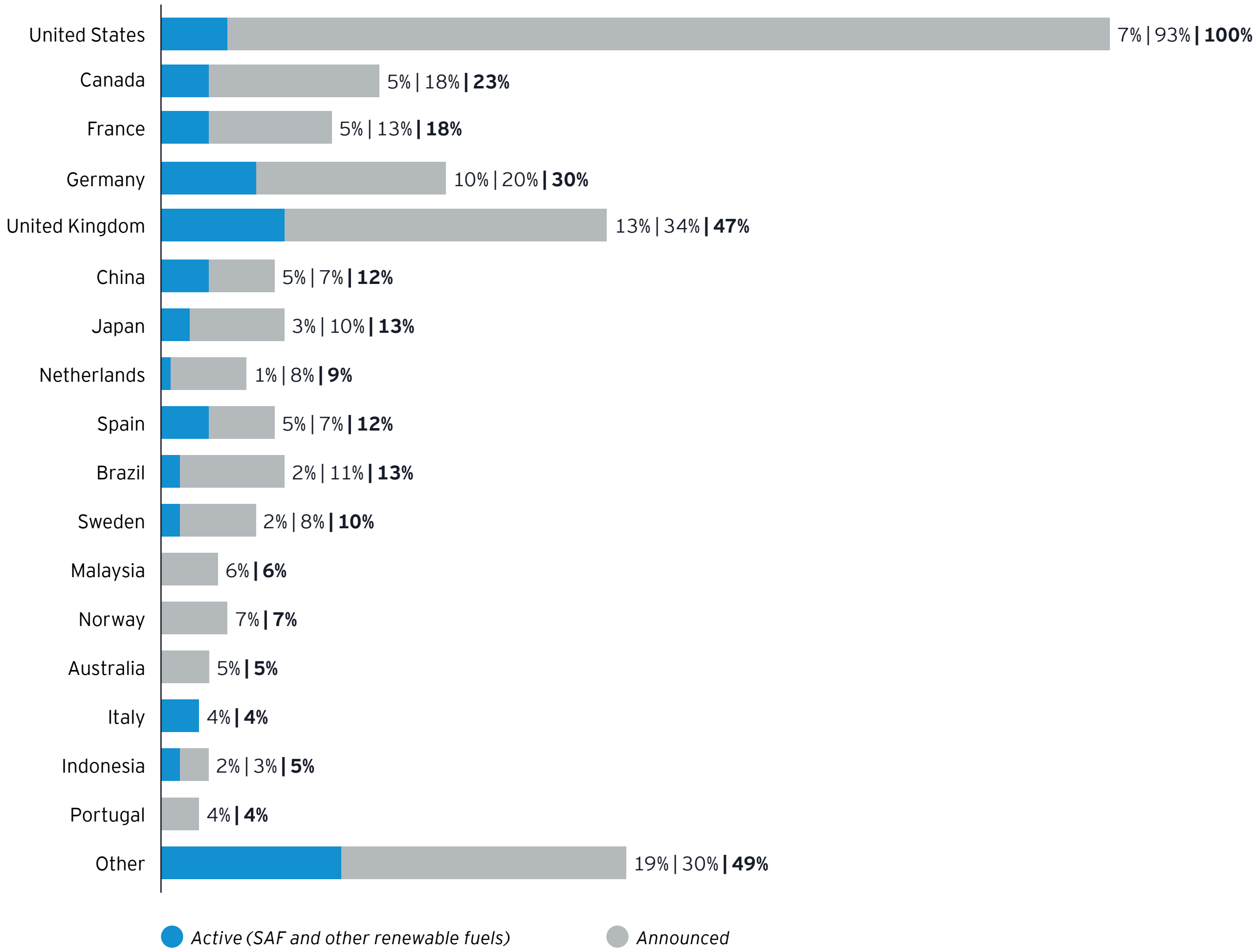
> Testing of the technologies in smaller projects is mainly focused on Europe, where the necessary expertise and technical infrastructure are available. The strategic implementation of this technology in larger projects in developing countries will make sense as soon as the necessary infrastructure has been established there.

Bernhard Dietrich, Head of CENA Hessen, Hessen Trade & Invest GmbH

Figure 25

Number of SAF projects by country; countries with three or fewer projects are summarized under "Other"[64]

(as of January 2025)



North America

The USA has the ideal conditions for ramping up SAF production. This is also reflected in the already comparatively high production volumes. The good suitability is based, among other things, on the extensive availability of agricultural land that can be used for the cultivation of biomass. According to the WEF, the acceptance of raw materials that potentially compete with food production is also greater in the USA than in Europe.

Furthermore, renewable energy is available at favorable prices in some states, such as Texas and California. However, there is a problem in that the regulatory framework in the USA primarily favors biodiesel over SAF. As a result, most existing plants for renewable fuels and renewable diesel are aimed towards the production of biodiesel. A key reason for this development is the blending mandate for biodiesel under the RFS (Federal Renewable Fuel Standards), which applies to road transportation.[95]

LanzaTech is a company in the USA that specializes in the production of E-SAF. It uses innovative technologies to convert industrial emissions into alcohols, which are then further processed into SAF. This AtJ technology was developed in collaboration with the U.S. Department of Energy and the Pacific Northwest National Laboratory. LanzaTech aims to contribute 10% of the world's SAF production capacity after commissioning and to provide double the amount of the previous SAF production in the United States.[96]

Other exemplary production projects in the USA include World Energy. This was the first company on a global scale to start producing SAF. In 2022, World Energy was involved in the first carbon-neutral flight.[97] The following year, together with Gulfstream Aerospace Corp., the company realized the first transatlantic flight with 100% SAF, pure HEFA-SAF, which contained no additional aromatics or other additives.[98] World Energy's ambitious purpose is to produce 1 billion gallons (approximately 3 million tonnes) of SAF annually by 2030.[100]

In Canada, SAF production is also experiencing significant momentum, supported by the adequate availability of biomass. By prioritizing the available biomass for the aviation sector, the total demand in Canada could be met by 2030.[99]

Europe

Even though Europe lags well behind North America in terms of its production volume, both today and future forecasts, a similar number of production facilities are expected. According to announcements by producers, Europe could contribute almost 20% of global SAF production by 2030. It is expected that production capacities for SAF in Europe could increase to 9.5 million tonnes by 2030, driven by the planning and construction of numerous new SAF production facilities.

As the figures below illustrate, Germany is projected to experience a significant rise in its maximum SAF production potential. While there was only a production of 0.01 million tonnes in 2024, the capacity could increase to 1.53 million tonnes of SAF by 2030.

In Europe, for example, there are several projects and collaborations that could make a significant contribution to increasing the supply of SAF. Altalto, a project in collaboration with Velocys, British Airways and Shell, is aiming for producing a large remove volume. This project includes the first commercial plant in the UK to convert waste into aviation fuel. From 2027, the plant in Immingham is expected to convert more than 500,000 tonnes of waste into aviation fuel each year, producing 48,000 tonnes of SAF and other transport fuels.[100]

> "Production capacities in Germany should have been strengthened by political incentives. We have lost several years due to the lack of such incentives but are now on the right track to raise production.
>
> **Jan Eike Blohme-Hardegen,** Head of the Environmental Department, Hamburg Airport

In the area of E-SAF, Norsk e-Fuel is aiming to build Europe's first commercially scalable plant for H_2-based SAF in Norway (Herøya, Porsgrunn). With a focus on PtL technology and the exclusive use of 100% renewable energy, the company aims to be a pioneer in environmentally friendly fuel production. Norsk e-Fuel is a consortium consisting of four partners. Among them is Climeworks AG, a pioneer in the technology of CO_2 capture from the atmosphere. The annual production capacity is 8,000 tonnes. This capacity is to be increased to 80,000 tonnes and can be scaled up further.[101]

Despite these positive expectations, the expansion of SAF availability in Europe faces challenges. The high population density in the region generally limits the availability of agricultural land. These obstacles are further exacerbated by a general lack of biomass raw materials in Europe, which additionally limits the production capacity for Bio-SAF. The availability and costs of renewable energy sources – particularly solar and wind energy – are also constraining factors in Europe. Consequently, the WEF anticipates that, in addition to expanding production capacities, the import of SAF will play a significant role. According to the WEF, European producers and consumers expect that intensive collaboration both within Europe and internationally will be essential to meet the SAF demand.[97]

Figure 26

Comparison of expected potential production capacities of SAF by 2030 in million tonnes (worldwide, Europe, Germany)[64]

(as of January 2025)

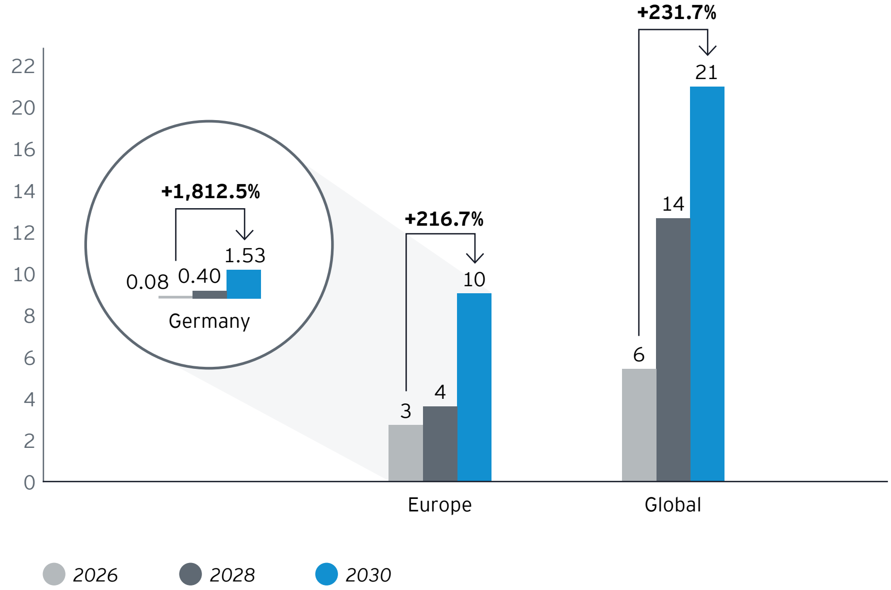
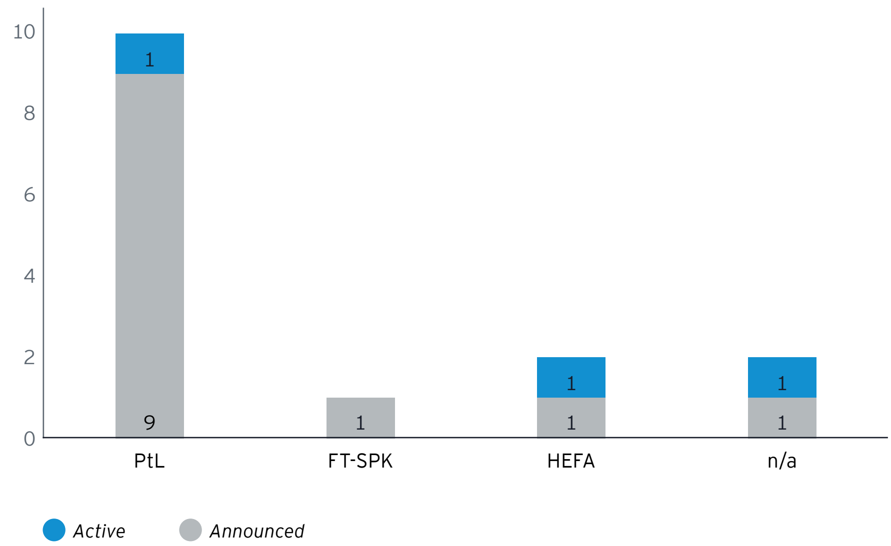


Figure 27

Number of SAF projects in Germany by activity status and production technology[64]

(Source: Argus SAF production capacity, as of January 2025)



Capacity

Africa
SAF production has not yet taken place in Africa. One challenge in establishing SAF production on the continent is to develop sustainable supply chains for raw materials. Inadequate infrastructure, limited refinery capacity, and insufficient regulatory frameworks present significant challenges, often leading to project delays and increased costs.

Nevertheless, SAF production in Africa has great potential, partly due to the high availability of suitable biomass such as waste.[102] The EU is planning to support feasibility studies and certifications for SAF production in 11 African countries with a budget of €4 million (~US$4.32 million). The development of local production capacities for SAF will reduce costs in the long term. Companies such as Eni from Italy, Sasol from South Africa, Linde from Germany and Topsoe from Denmark are already driving investments in SAF and biofuels in Africa. An environmental manager at the African Civil Aviation Commission expects SAF production to start in at least two African countries within the next few years, with prospects of expansion to a third country. He names Kenya, South Africa and Ethiopia as likely candidates for this development.[103]

Central and South America
Even though Central and South America has so far produced the smallest amount of SAF after Africa, the region still has potential for strong future growth. Brazil's influential biofuels industry, for example, offers a strong basis for bio-based SAF production. The country is already a leader in the production of biofuels for other means of transportation. It is to be expected that this strong position will also transfer to the production of SAF.[104] Brasil BioFuels is a good example of this. The company already operates several production plants to generate renewable fuels and is planning to open another plant by 2026. The production capacity is expected to be up to 0.4 million tonnes of fuel per year, including SAF using the HEFA process.[105]

APAC, Near and Middle East
SAF production is also being increasingly expanded in the Asia-Pacific region as well as in the Near and Middle East. There is a significant presence of potential raw material suppliers and refineries here, making the region a promising location for SAF production. Overall, according to the Air Transport Action Group, the Asia-Pacific region has the highest availability of SAF feedstocks in the world, with a significant share coming from industrial emissions.[106]

Singapore, for example, is one of the few countries with an established, operating system in SAF production. Most of facilities here are operated by Neste, the largest supplier of SAF worldwide.[107]

In addition, countries with a strong agricultural and biofuel production such as China, Malaysia and Thailand are likely to emerge as important suppliers of raw materials for SAF.[108]

Australia also stands out as a country with exceptional potential for SAF due to its diverse range of raw materials and feedstocks. Significant quantities of animal fat, cooking oil and rapeseed are exported to the EU, Singapore and the USA, where they are often processed into sustainable biofuels. In the future, these raw materials could also be used for the local production of SAF. In addition, Australia has enormous potential for the production of renewable energy and green H_2.

The construction of wind and solar plants is planned on an area of 6,500 square kilometers in the northwest of Australia. If the project reaches its full capacity, it will be possible to generate a total output of 26 GW and produce 4.5 million tonnes of green H_2 annually. To date, there are no PtL activities in Australia; however, this could change drastically with the increased availability of green H_2.

4.3 Existing production gaps and possible solutions

It is expected that the limiting factor for the widespread adoption of SAF will not be interest or demand, but rather availability[109]. Currently, all produced SAF is being utilized, and the demand from airlines even exceeds the current supply market.[110] Experts fear that a significant supply gap for SAF could emerge in the long term.[111, 92] Given current production capacity and the existing pace of expansion, it is unlikely that the projected demand of 104 million tonnes by 2040 and 195 million tonnes by 2050 will be met.

However, this assessment cannot yet be verified with concrete data, as plans for future production facilities do not extend beyond 2030. For this reason, the supply and the resulting gap in demand cannot be accurately predicted in the long term.

In the medium term, for the year 2030, a total global demand of 49 million tonnes of SAF is forecast.[112] According to the announcements on the planned construction and commissioning of plants to produce renewable fuels such as SAF, the maximum possible production capacity for SAF in the same year will be around 30.4 million tonnes.[64] It would, therefore, theoretically still be possible to meet the expected demand in 2030. It should be noted that the maximum production capacity, as explained in Chapter 3.1, can only be achieved if the production of SAF is prioritized over that of other fuels.

Unfortunately, this is not the case under the existing regulatory and economic conditions. For this reason, it is expected that without new regulatory incentives for SAF production, there will already be a supply gap by 2030. However, it may be smaller than the gaps that could arise in the following decades. This projection is supported by industry experts; for example, the WEF concludes in a report that by 2030, only about one-third of the SAF demand may be met.[97]

The main reasons for the limited supply are technological limitations, particularly in E-SAF production, the limited availability of biomass as a raw material for bio-based SAF and the generally high costs of SAF production. In addition, competition with other renewable fuels produced in the same process routes also has a significant effect.

Figure 28

Possible demand fulfillment under maximum utilization of SAF production capacities in 2030

(Source: EY, as of January 2025)

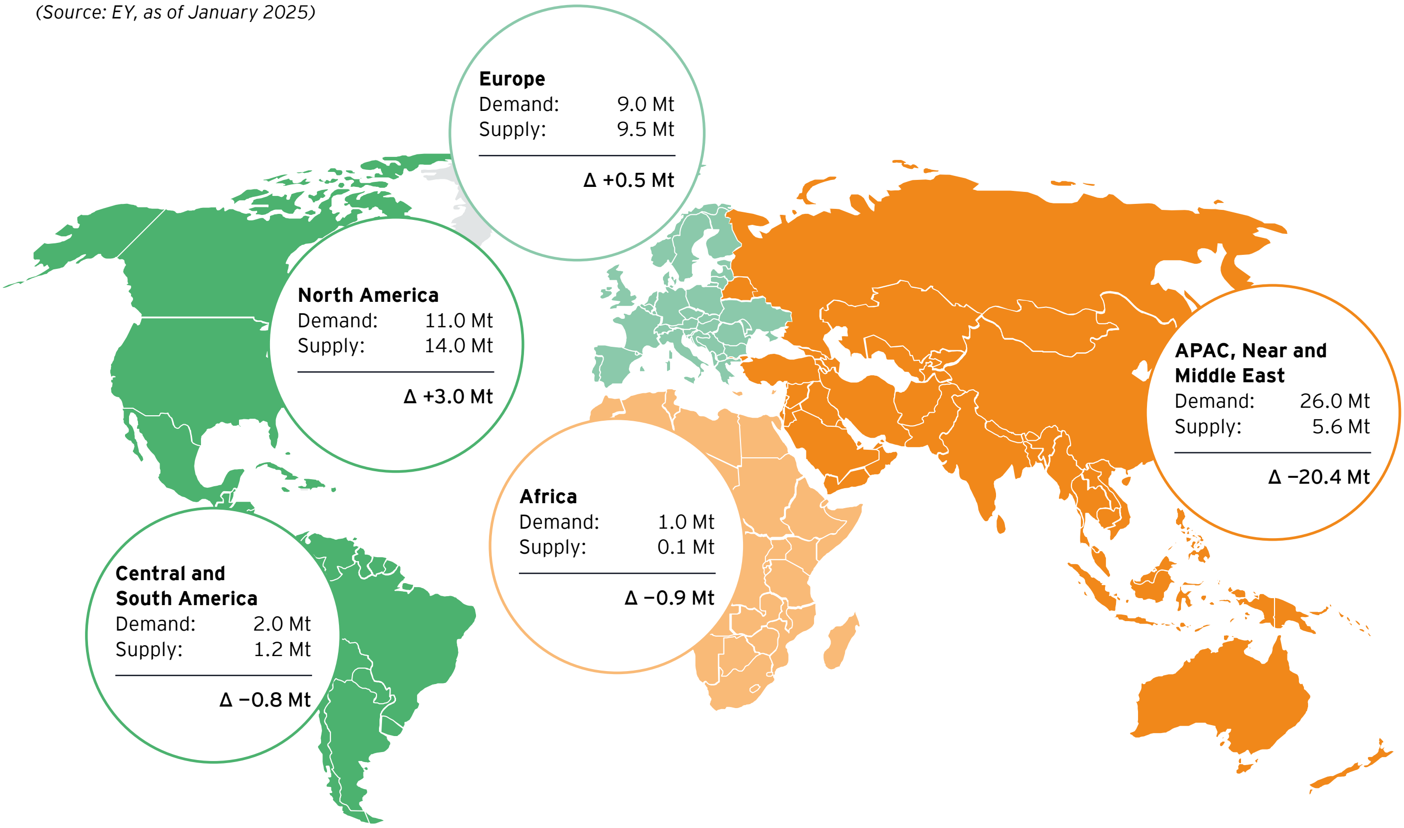


Figure 28 illustrates the regional differences in demand fulfillment and the expected production gaps in 2030. When interpreting the data shown, it should be noted that the supply represents the maximum possible production volume. However, as previously explained, this is a very optimistic representation since maximum supply is unlikely to be fully achieved.

If SAF production facilities were operated at maximum capacity, North, Central and South America could potentially generate surplus of 2.2 million tonnes by 2030. Similarly, Europe could theoretically meet its forecast demand of 9 million tonnes with a slight production surplus. However, since these maximum production capacities will likely not be fully utilized in practice, these surpluses may not materialize in all three regions. Industry experts anticipate that Europe, for example, will continue to depend on SAF to satisfy its domestic demand.[97]

In Africa, forecasts indicate that demand cannot be met even under maximum production scenarios. Although the continent's projected demand is relatively low at 1 million tonnes compared to global figures, potential production is expected to reach only 0.1 million tonnes — falling significantly short of anticipated growth. The outlook is even worse for the Asia-Pacific region and the Near and Middle East. Here, the SAF production will remain at a volume of less than 5.6 million tonnes. Demand, on the other hand, could be 26 million tonnes by 2030, which would lead to a considerable production gap of almost 20.4 million tonnes of SAF.

Unfortunately, it is not possible to make a concrete prediction of actual global or regional SAF production volumes due to the lack of data. However, a detailed EY analysis of the selectively available data suggests that actual SAF production will fall well short of maximum capacity. This is in line with the estimates of other experts. Out of 21 SAF projects, which account for 80% of the announced production capacity, there is data for only eight of them that indicates how much of the maximum capacity will be allocated to the production of SAF. Figure 29 provides an overview of this data. As shown, there is considerable variation among projects in terms of the share of production capacity allocated to SAF. Several planned facilities are expected to primarily produce other renewable fuels, meaning that SAF output may account for only around 20% of their maximum capacity. On average, the eight assessed plants are projected to utilize approximately 62% of their maximum SAF production capacity. However, this figure should be interpreted with caution, as it is neither representative nor generalizable due to limited data availability.

If it becomes evident that this trend continues globally across the majority of announced SAF projects, it is expected that by 2030, not only the Asia-Pacific region, the Near and Middle East, and Africa will be unable to meet their SAF demand from domestic production. A similar situation could arise for Europe, and even the American continents might only be able to barely meet their SAF demand under such circumstances by 2030.

In order to fully cover the expected future total demand in the long term, there would have to be exponential growth in SAF production worldwide.[113] To achieve this, it is necessary both to increase the maximum production capacity by building new plants and to prioritize the production of SAF over that of other sustainable fuels in order to make full use of this maximum capacity.

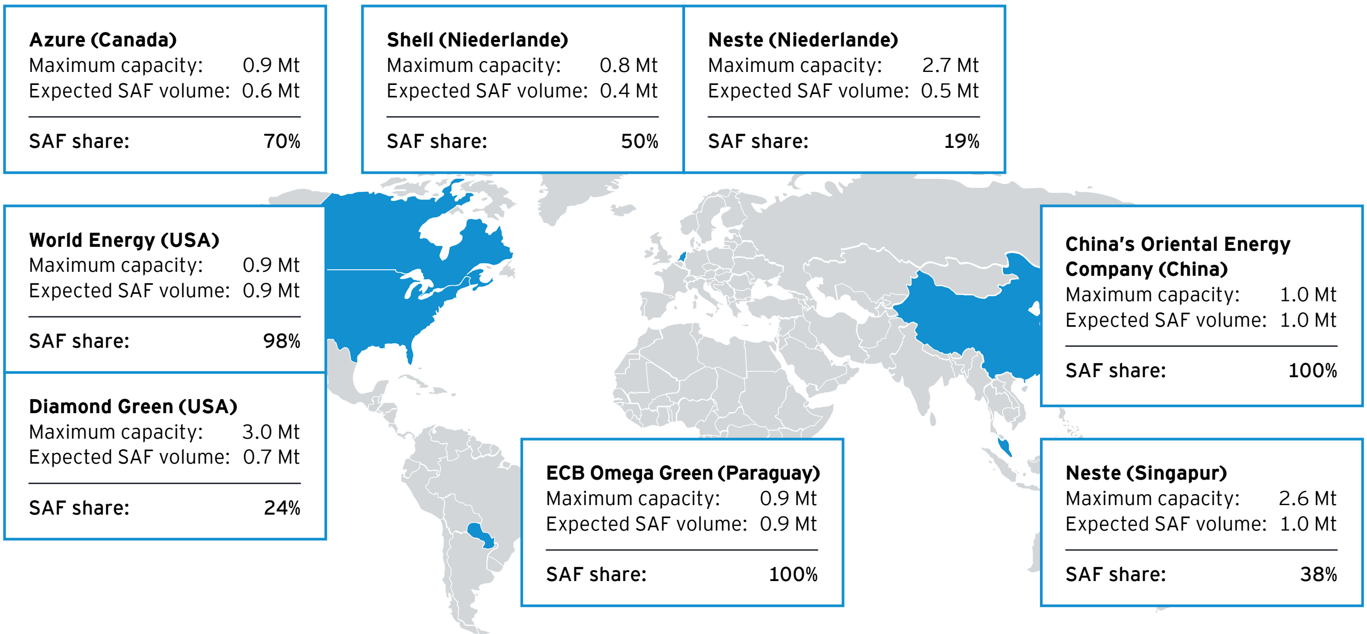
Such prioritization of SAF can be brought about either by incentives created by the market or by government regulations.[114] High investments in production facilities are required to expand capacities. To cover the forecast demand, the number of production plants would need to increase by 5,000 to 7,000 units by 2050. This would result in a cumulative investment requirement of 1.0 to 1.5 trillion US dollars. This would correspond to an annual global investment requirement of 6% to 10% of the current annual investment in oil and gas infrastructure.[67]

production facilities

Figure 29

Comparison of the maximum possible SAF production shares and the actual announced volume for selected production facilities

(Source: EY, as of April 2024)



The WEF identifies five concrete measures that would be necessary for the successful global scaling of SAF production and projects[97]:

- **Rapid technological development:** Increased investment in research and the further development of production technologies is necessary to enable a production ramp-up at competitive prices. Due to the long planning and development times for production facilities, it is essential to act quickly and invest the necessary resources.

- **Net-zero corridors:** For an efficient ramp-up, it is essential to establish specialized infrastructure for the trade and transport of SAF between the main producers and the customers. These so-called net-zero corridors should connect areas that offer a high availability of raw materials with those that are particularly suitable for production, as well as with the customers.

- **Partnerships and collaborations:** It is already clear that collaboration is an essential factor in driving forward the expansion of SAF. This must be further intensified in the future in order to bundle interests and ensure long-term planning security. The cooperation of the financial sector in the form of provision of financing options is also important here.

- **Regulation and incentives:** The favorable prices for fossil fuels make it unlikely that market dynamics alone will make SAF production sufficiently attractive. For this reason, regulatory incentives are needed that either make fossil fuels less attractive (e.g., taxes or penalties) or make SAF more attractive or even mandatory (e.g., SAF quotas in the EU). In addition, the creation of new state financing options can boost SAF production by ensuring economic competitiveness. International coordination is also necessary here to prevent the relocation of activities to countries with less stringent requirements ("carbon leakage").

- **Standardization of book-and-claim systems:** Standardized systems are necessary to ensure the reliable and clear accounting of CO_2 savings through SAF use. This applies to the supply contracts explained in Chapter 3.3, where, in the absence of suitable infrastructure, one party purchases SAF and accounts for it on its own balance sheet, while another party physically fuels the aircraft with the fuel.

Necessary logistics and infrastructure

5

Introduction and summary of the chapter

According to IATA, the SAF share of global aviation fuel use in 2024 was just 0.3%.[116] This is largely due to the still high price premiums and limited production capacities for Bio-SAF. To expand the production of SAF, the production and distribution infrastructure must be expanded. Considerable investment in infrastructure is needed to produce and distribute SAF competitively. Strategic infrastructure upgrades can enhance both the efficiency and climate impact of producing fuels such as SAF.

Due to the strong similarity between blended SAF and conventional kerosene, the existing distribution infrastructure can continue to be used. The production infrastructure, on the other hand, requires adjustments. At present, the SAF-specific infrastructure along the global supply chain is still very limited, so it seems likely that existing infrastructure for conventional jet fuel will be used to minimize costs and time.[116]

In the context of SAF logistics, the applicable regulations and standards are of central importance. Reference is made to the latest version of ASTM D7566, which regulates the quality testing of SAF prior to blending, and to ASTM D1655, which is responsible for the quality testing of the finished aircraft fuel blend. In addition, the guidelines of the Joint Inspection Group (JIG) – in JIG 1, JIG 2 and EI/JIG 1530 – should be emphasized, which are decisive for quality assurance and operating standards along the entire aviation fuel value chain. These standards play a decisive role in the design of the infrastructure and ensure compliance with the highest quality and safety standards.[115]

SAF is usually produced at different locations than conventional kerosene. At the refineries, SAF is stored in separate tanks that are no different in design from those used for conventional jet fuel. Coordination with the refineries is crucial to ensure the pipeline transfer of SAF to the airport. The value chain for SAF can be divided into the following main phases[116]:

1 | Production of the oil intermediate and possibly direct production of SAF in the refinery

or

2 | Transport of the oil intermediate to another refinery for the production of SAF

3 | Blending directly at the production site if SAF infrastructure and conventional kerosene are available

or

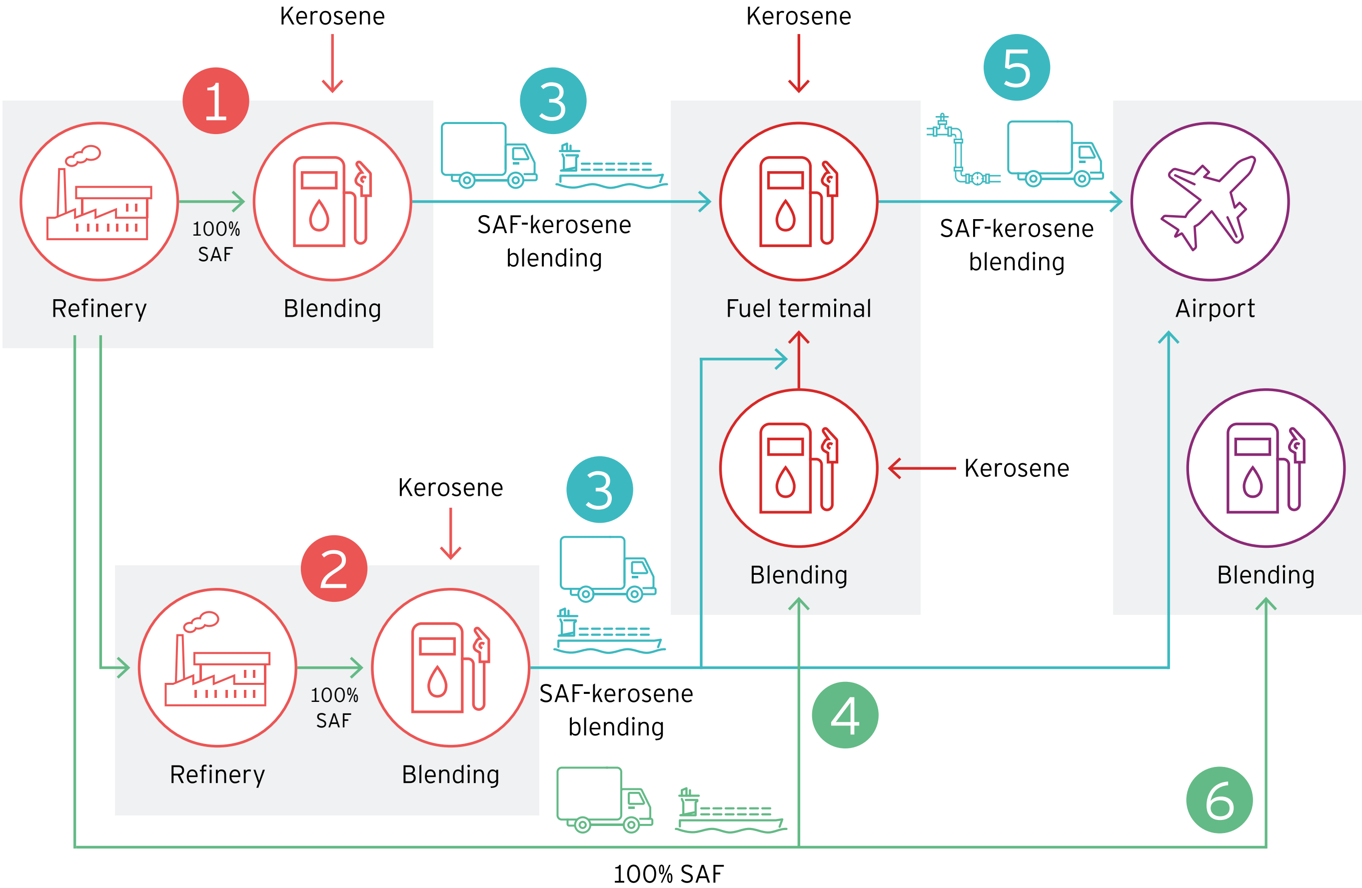
4 | Forwarding to an intermediate location (e.g., fuel terminal) if there is no access to conventional kerosene or blending infrastructure

5 | Transportation of the SAF to the airport

6 | Possibly also blending directly at the airport

Figure 30

General SAF infrastructure along the supply chain (presentation according to ICAO)



The production infrastructure for bio-based SAF includes relevant processes such as raw material sourcing, collection, storage and processing of biomass, transportation and the refining and production process. The production of biomass is divided into five steps

1 | Harvesting and collecting biomass
2 | Pre-treatment
3 | Transportation
4 | Conversion to liquid fuel and
5 | final use is divided, with each of these steps being significant for the production of Bio-SAF.[117]

The production of E-SAF is based on access to renewable energy. In countries like Chile, South Africa, and Morocco, E-SAF production can be significantly cheaper due to particularly favorable geographical conditions compared with Germany and other European countries. However, expanding electricity generation from renewable sources can pose an additional challenge, especially regarding the availability of sufficient land area.[118] In addition to the availability of renewable energy sources, innovative technologies for electrolysis and CO_2 capture are required for E-SAF production. Electrolysis capacity must be ramped up globally to meet the increasing demand for H_2.

Three electrolysis methods are distinguished, each with different infrastructure requirements: alkaline electrolysis, polymer electrolyte membrane electrolysis, and emerging technologies such as solid oxide electrolysis.[119] The commissioning of a variety of DAC facilities to extract CO_2 from the atmosphere or infrastructure for the indirect capture of CO_2 from biogenic sources is also essential. SAF can be blended with conventional kerosene either at production sites or directly at airports. Currently, blending at refineries or by SAF producers is the preferred approach (see Figure 30). The choice of blending option depends on the available facilities, costs and complexity. Both approaches offer advantages and disadvantages in terms of costs, control and complexity. The blending of SAF and conventional kerosene can be carried out using different models. With segregation, conventional kerosene and SAF are transported separately to the airport. With mass balance, SAF and kerosene are mixed and then transported together. The book-and-claim system (virtual) makes it possible to fulfill the sustainability requirements of aircraft fuel via certificates that can be purchased. No physical separation of SAF and kerosene is necessary.[120]

The core infrastructure at airports for the provision of SAF is crucial to facilitate its use and integration. As SAF is compatible with existing infrastructure, many existing facilities can be used. The core infrastructure consists of the following components:

1 | Logistics and transportation: Logistics comprises the transportation of SAF from the production sites to the airports. This can take place via various means of transportation such as pipelines, trucks, trains or ships.

2 | Storage and tank system: The storage of SAF at airports requires appropriate tank systems. The possibility of storing SAF separately from conventional kerosene enables better control over fuel quality. There is also the option of storing both types of fuel in separate tanks and only mixing them before refueling the aircraft.

The various transportation options offer different advantages and disadvantages:

- Truck transportation proves to be flexible and cost-effective for smaller quantities but requires additional infrastructure for larger volumes.
- Rail transport enables the transportation of larger quantities but requires an existing rail infrastructure.
- Shipping is suitable for transporting large volumes but requires port infrastructure close to the airports.
- Pipeline transport is a cost-effective form of transportation due to its low operating costs but requires special permits and investment in infrastructure.

The decision for a transportation method depends on various factors such as costs, availability of infrastructure and environmental impact.

This chapter takes an in-depth look at the central infrastructure required for the production of SAF. Particular attention is paid to the different characteristics and requirements of the production infrastructures for organic and E-SAF. It also examines the infrastructure on the customer side, which is identical for both types of SAF and therefore provides a common basis for distribution and use.

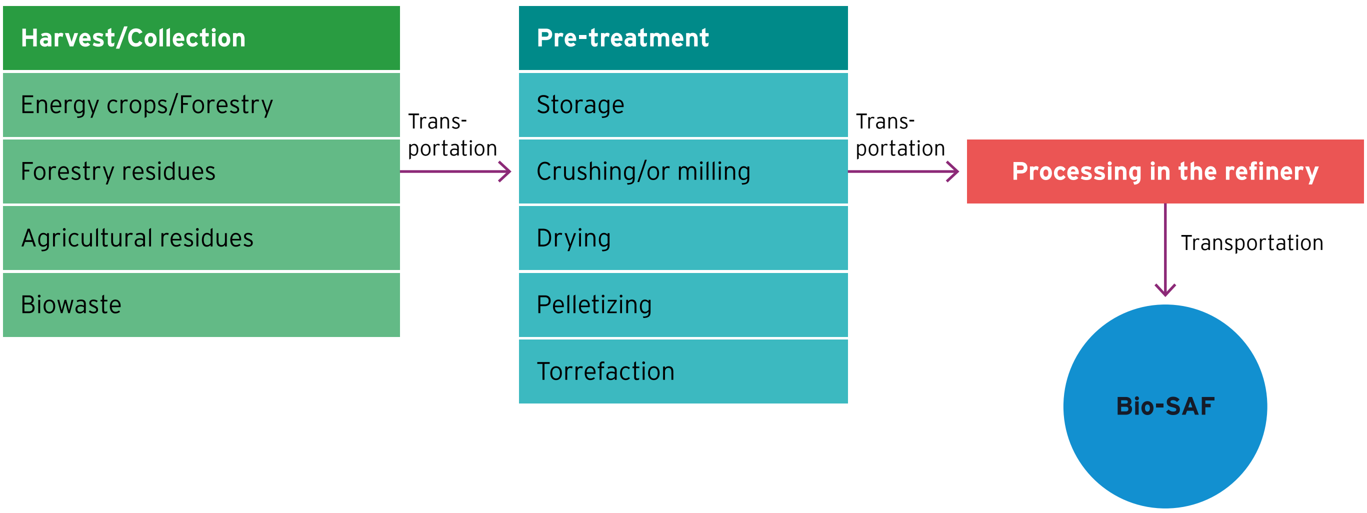
5.1 Core infrastructure on the producer side

SAF can generally be transported from the production site to the customer using the same infrastructure and logistics as conventional aviation fuels. However, SAFs are often not produced at the same location, so they are usually transported to the end consumer by truck, rail or ship. SAF is stored in separate tanks in the refineries and is not mixed, although these tanks generally do not differ in design. The aviation fuel is then from this place transported to the airport via pipelines, whereby agreements with the refineries are necessary to enable the transportation of SAF.[118] The main differences lie in the production methods and facilities. For Bio-SAF, the production infrastructure must be expanded in terms of raw material sourcing, transportation, refining and production. According to estimates from the DEPA2050 study, 5,000 to 7,000 refineries are needed to produce the required quantities of SAF.
In addition, appropriate infrastructure is required for the collection, storage and processing of biomass. Waste management and renewable biomass preparation play a central role here. The production of biomass and its logistics comprise many components that facilitate the conversion of primary biomass sources into final products for bioenergy. The IEA divides this process into five phases (see Fig. 31):

1 | Harvesting and collection of biomass (harvesting processes, collection)
2 | Pre-treatment (storage, crushing, drying, pelletizing, torrefaction)
3 | Transportation (by truck, rail and ship)
4 | Conversion to liquid fuel
5 | Final use

After the harvesting and collection of first- and second-generation biomass (1), the material undergoes a pre-treatment process (2). This step involves converting the solid biomass to enhance energy density, improve transport efficiency, and reduce associated logistics costs. First, the biomass is transported to a temporary storage site. Potential compaction processes are baling and shredding. Baling, especially for straw, serves to minimize transport and storage costs due to the originally low energy density of the straw. Shredding processes include chopping and grinding. Another treatment step is drying the biomass to reduce transportation costs. Reducing the moisture content not only increases combustion efficiency but also prevents the growth of fungi. Technologies for drying the material include rotary drum dryers, fluidized bed dryers, and steam-operated dryers. Further pre-treatment steps include pelletizing to compact the biomass and torrefaction, in which the biomass

Figure 31
Biomass production and logistics[119]



heated to 200°C to 300°C in the absence of O_2. Torrefaction breaks up the fibrous structure to give the biomass coal-like properties. Storage of the biomass is necessary due to seasonal production and to ensure a continuous supply. Storage supports the air-drying of the biomass. Regular circulation can minimize the high risk of fire due to bacterial activity.[119] Transport costs are often high compared with fossil fuels due to the low energy density of biomass. Therefore, it often makes sense to locate the biorefinery plant close to a biomass collection point. Transport (3) by truck is used for short distances (< 100 km) to allow flexibility when reaching several small production sites. Rail transport is used for longer overland distances. Transport by ship (dry bulk transporter or tanker for liquid biofuels) is suitable for long distances and large quantities and proves to be the cheapest and least energy-intensive transport mode.[119] After preparation of the intermediate product, the biomass is further processed into SAF (4), depending on the intended conversion route as shown in Figure 2 to Figure 7 (Chapter 1.1.1), so that the SAF is then available for final consumption (5).

The production of E-SAF requires renewable energy that can be generated by solar or wind power plants, as well as electrolysis and CO_2 technologies. The existing infrastructure for conventional aviation fuel production can be repurposed for the production of E-SAF.

This also includes distribution and refueling infrastructures such as tank farms, tank trucks, pipelines and filling stations.[121] When it comes to the generation of renewable energy, it is important to look primarily at regions where sufficient production capacity is available and extended land use for electricity generation is possible. In order to be able to produce E-SAF in accordance with the ReFuelEU Aviation sub-quota in Germany and Europe, the following steps must be taken by 2032:

- Identification of new production sites and availability of space
- Provision of additional electrolysis capacities of 0.9 to 1.8 GW (the installed electrolysis capacity in 2022 was around 1.4 GW)
- Increase in electricity capacity from renewable energies

For example, to achieve the EU objective of E-SAF in 2032, an area of around 195 square kilometers would be needed for photovoltaic systems (solar panels). The implementation of onshore wind farms would require an even larger area — an estimated 430 square kilometers — to maintain the required distances between the turbines to maximize the efficiency of the wind farm.[75] There are various scenarios for electricity generation from renewable energies. In Germany alone, around 7.5 terawatt hours (7,500 GWh) would have to be produced in order to meet the 2% regulation for 2032.

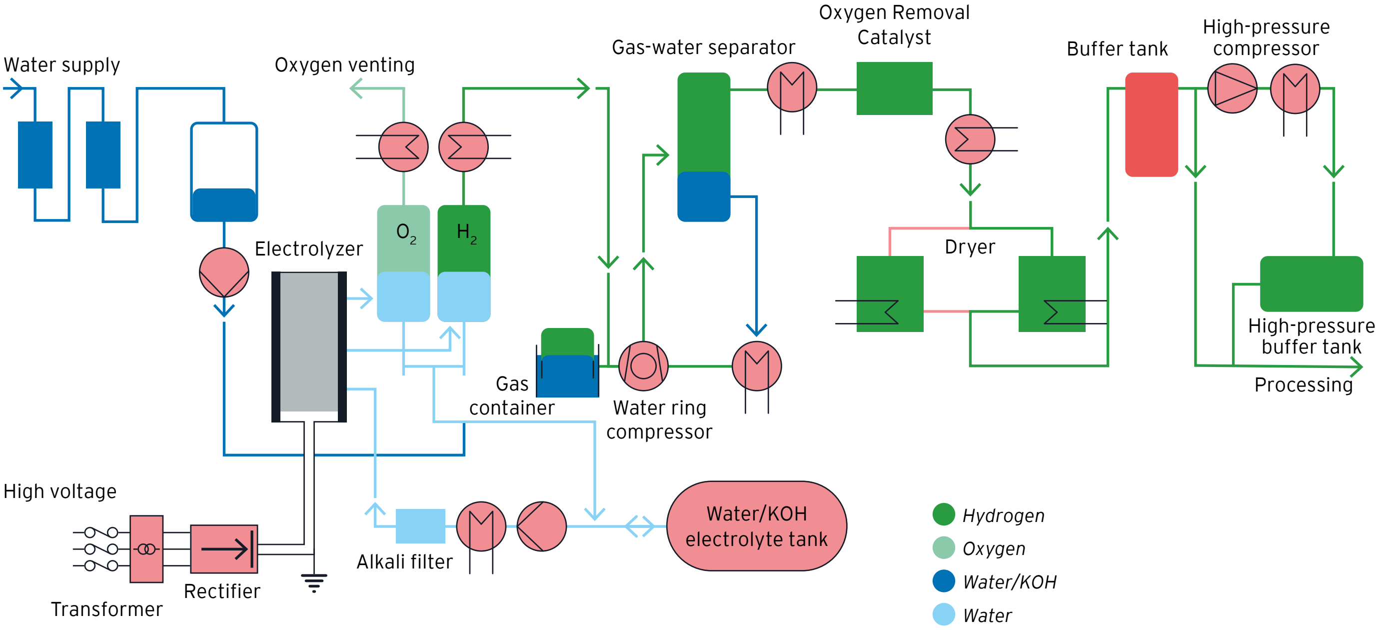
The electrical power generated from solar and wind energy has a volatile profile; however, continuous availability is required for the production of E-SAF. For this reason, it is likely that PtL plants will integrate H_2 storage as a buffer for short-term fluctuations. Options for H_2 storage include pressurized tanks, storage pipelines and salt caverns. In the long term, technical and economic considerations will determine whether H_2 is stored or whether subsequent conversion processes are designed enable flexible operation in line with load requirements.[121]

The central conversion of renewable energy into chemical energy takes place through electrolysis, a process in which water is split into H_2 and O_2. As already mentioned, there are various electrolysis methods: alkaline electrolysis, poly-membrane electrolysis and emerging technologies such as solid oxide electrolysis. Each technology places different demands on the infrastructure.[121]

Alkaline electrolysis is the most widely used technology within the group of low-temperature electrolyzers.[75] A liquid alkaline solution of sodium or potassium hydroxide is used as the electrolyte, which has been commercially available for many years. Electrocatalyst-loaded electrodes are used in a typical industrial configuration. A diaphragm made of solid, porous oxide enables the ion transport of OH- between the electrodes, whereby the diaphragm also separates the electrolytes, H_2 and O_2 gases. There are two main types of cells for electrolysis: the simple tank cell (unipolar) and the filter press cell (bipolar). Electrolysis takes place in a temperature range of 50°C to 80°C and at pressures of up to 30 bar.[122]

Figure 32

System design of alkaline electrolysis[123]



Proton exchange membrane (PEM) electrolysis has become established due to its higher load flexibility compared to other low-temperature electrolysis technologies.[75] It uses a solid polymer electrolyte, operating at pressures of 20 to 40 bar and temperatures between 50 and 80°C, thus under similar conditions to alkaline electrolysis. The system design is simpler and more compact compared to the alkaline electrolysis, allowing for operation at higher current densities.

Due to the aggressive oxidative conditions and high voltages, titanium-based materials, precious metal catalysts and protective coatings are required. Accordingly, the PEM electrolyzers are more expensive than alkaline electrolyzers.[125] The system's advantage is that it can operate under different pressures, which reduces costs and minimizes system complexity and maintenance.[125]

Solid oxide electrolysis (SOEC), also known as high-temperature electrolysis, is characterized by high efficiency values. One type of SOEC is co-electrolysis, which uses both CO_2 and water vapor to form synthesis gas. So far, SOEC systems have only been implemented in smaller demonstration plants.[75]

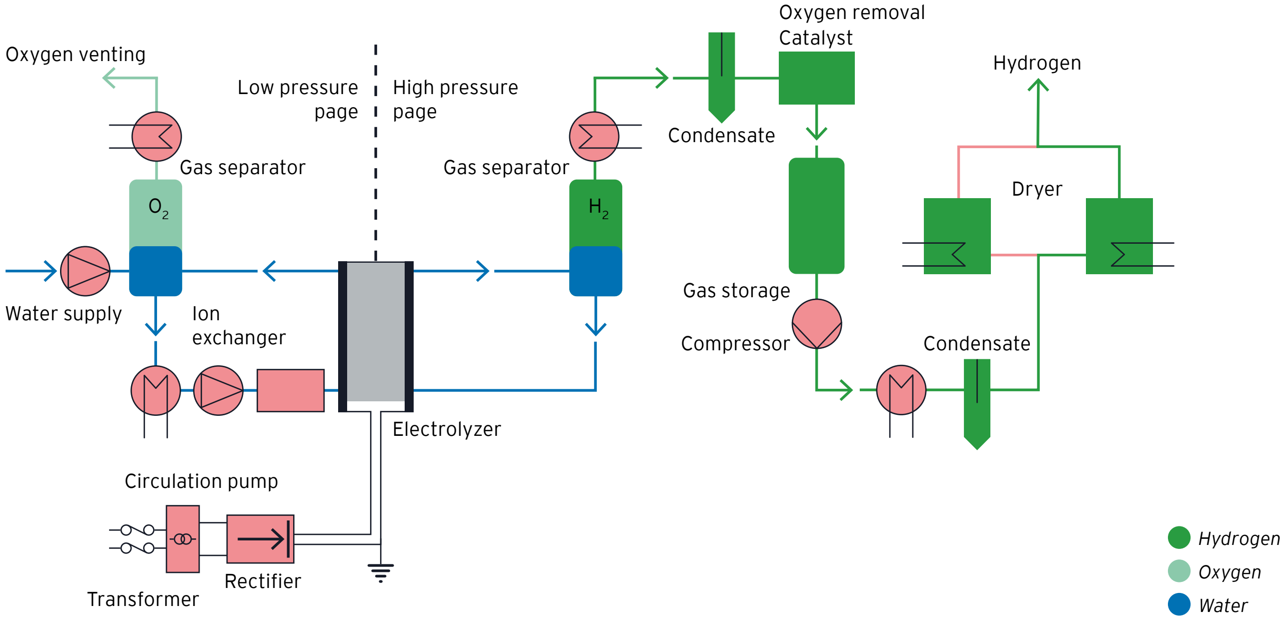
Solid oxide electrolyzers operate at high temperatures (700°C–850°C). Under these kinetic conditions, the use of inexpensive nickel electrodes is possible. The SOEC can combined with systems that generate heat, which offers the advantage that the heat required for water evaporation can come from external sources, for example from waste heat from industrial processes or concentrated solar power plants.

Electrolysis

i Potassium hydroxide

Figure 33

System design of PEM electrolysis[125]



In particular, the combination of solid oxide electrolysis cells (SOEC) with concentrated solar power plants appears promising, as they can provide both electrical energy and the necessary heat.[125]

In this way, SOEC has the potential to significantly reduce energy consumption, for example by using the waste heat from processes such as Fischer-Tropsch synthesis.[121]

Furthermore, sustainable CO_2 is required as a raw material to produce E-SAF. A total of 1 million tonnes of CO_2 will be required to achieve the objective of an E-SAF quota of 2% in Germany by 2032 in accordance with the RefuelEU Aviation Regulation. This requires the commissioning of an additional 250 DAC plants, each with an annual production capacity of around 4,000 tonnes.

These plants are necessary to capture carbon either directly from the atmosphere or from bio-based sources.[75]

Figure 34

System design of the SOEC[125]

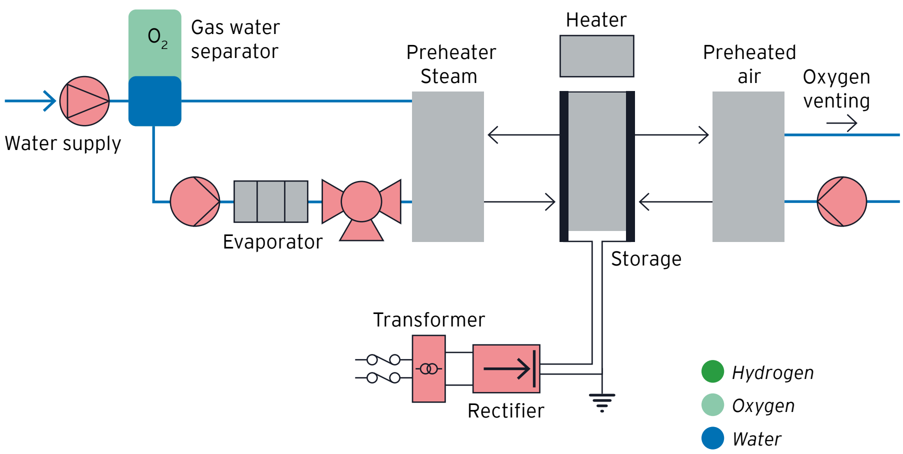
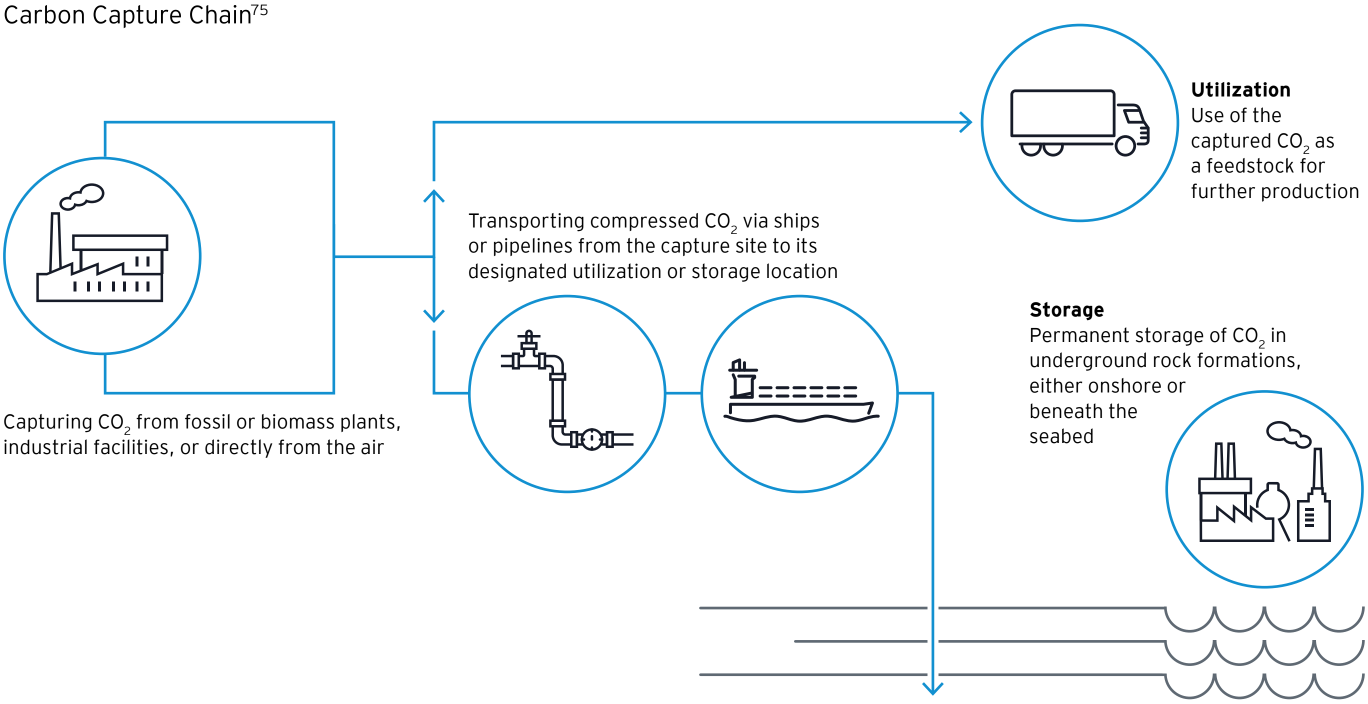


Figure 35

Carbon Capture Chain[75]



Another option is the indirect capture of CO_2 from biomass. Plants absorb CO_2 from the atmosphere by photosynthesis, which is then released in subsequent processing steps, such as the combustion of biomass or the production of biogas or bioethanol.

In contrast, direct CO_2 capture uses fans that draw air through a sorbent material.[i] This sorbent binds the CO_2, allowing it to be separated from the other air components. After adsorption, the CO_2 is released from the sorbent by applying heat.[75] Finally, the product is compressed for transport by ship or pipeline to the consumer or storage site.

The CO_2 is either used directly for the synthesis of E-SAF (DAC with carbon usage) or compressed for long-term storage underground (DAC with carbon storage).[75] The entire carbon capture process is illustrated in Figure 35.

Before bio- or E-SAF can be blended with kerosene (JET-A1), it must first be tested according to the standard specification ASTM D7566. The pure SAF can be easily controlled by the manufacturer, although the quality, such as the levels of aromatics and sulfur content, may differ from conventional kerosene.

For an optimal blend, both the conventional kerosene and the pure SAF must be tested. Preliminary tests are necessary to evaluate the final SAF-kerosene blend according to ASTM standards (see details in Chapter 1.2). Finally, the end blend must be retested and certified as aviation fuel according to ASTM D1655. This process typically requires two additional tanks (for SAF and the final blend), infrastructure and systems for fuel transfer, as well as a laboratory for verifying and certifying the fuel.

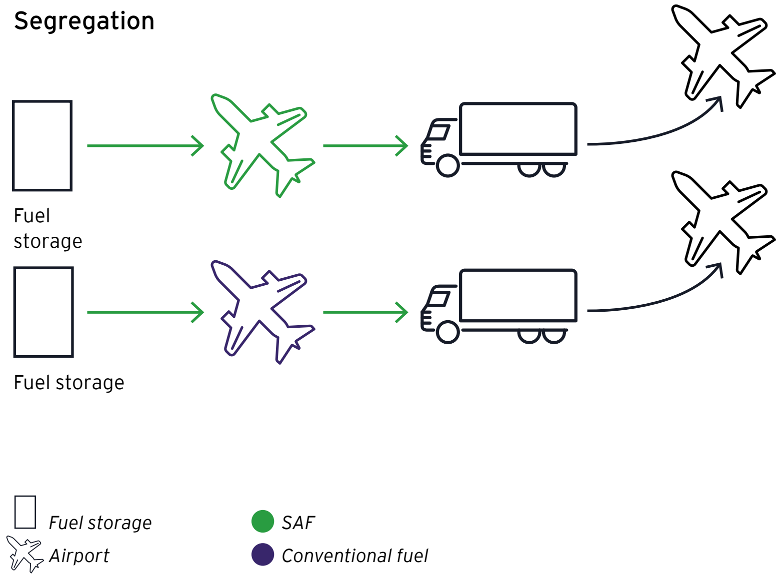
Furthermore, mechanical or hydrodynamic mixing is necessary; otherwise, due to the difference in density, an inhomogeneous mixture could occur.

CCS chain

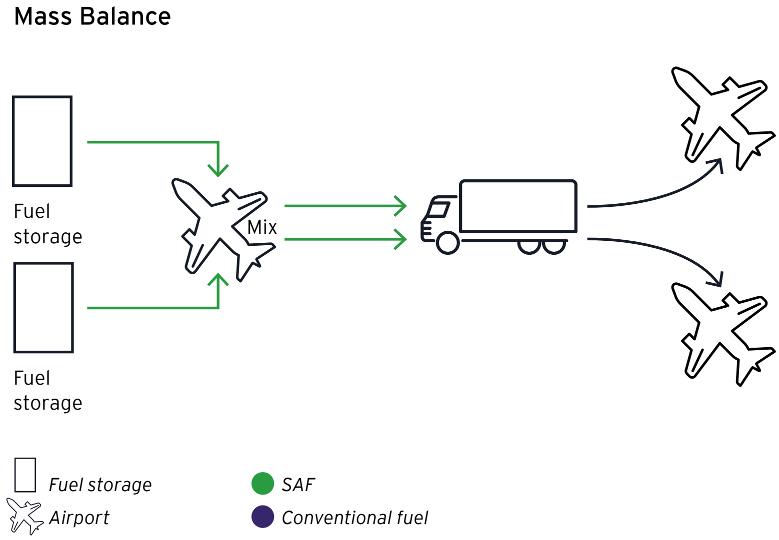
i Potassium hydroxide

Different types of SAF can be blended according to three models:

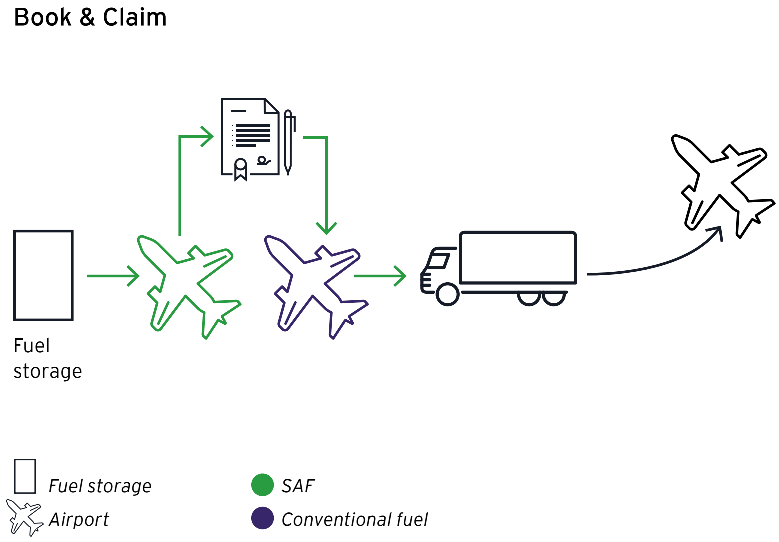
- **Segregation** describes a physical separation of conventional aviation fuel and SAF from the production site to the airport. This method is only sensible if the fuel production facility is located near the airport.[122] However, from a technical perspective, separation is not necessary, as so-called drop-in aviation fuels are compatible with petroleum-based aviation fuel and do not cause performance losses. Consequently, segregation would likely lead to additional costs due to the need for extra infrastructure. With fuel certified according to ASTM 1655, no fuel separation is required, and airports can treat SAF like any other aviation fuel.[124]



- **Mass balance** allows for the blending of certified SAF with non-certified kerosene within the existing infrastructure for transport, storage, and distribution. Throughout the entire supply chain, the proportion of certified aviation fuel is continuously monitored to ensure that only the originally transported amount of certified aviation fuel is accounted for at the end. With the mass balance, the certified components of the fuel can be tracked through every phase of the supply chain. This seamless traceability also enhances the ability to demonstrate the origin of raw materials and fuels, supporting additional sustainability criteria.[122]



- **The book-and-claim system** (only virtually) certifies the sustainability characteristics of a specific quantity of aviation fuel immediately after its production. These certificates can then be resold to credit buyers, who in turn can claim credits for SAF. A significant advantage of this method is that the certified aviation fuel can be seamlessly integrated into the existing supply of kerosene without the need for separate infrastructure for transport or distribution. This is because certified and non-certified kerosene do not require physical separation.[122]



> For the market ramp-up of SAF to succeed, it must be ensured that production meets and ideally even exceeds the blending obligations. Practical mechanisms such as book-and-claim can contribute to simple, transparent and credible use of SAF.

Melanie Form, Member of the Management Board and Managing Director, Aireg

The individual blending of either Bio- or E-SAF with JET-A1 can take place at a tank farm (and an airport) or at a production site (see Fig. 1-7 in chapter 1.1.1):

1 | Mixing at a tank farm has the following advantages and disadvantages:

Advantages:
- Greater capacity and space availability for mixing
- Extensive experience in dealing with bio-based SAF available
- Possible use of the available infrastructure for loading and unloading fuel and the downstream infrastructure to the airport
- Industrial plant as a suitable location
- Delivery of the final product to several airports possible
- Fewer trucks required
- Lower transportation costs
- Simplification of the fuel supply chain
- Promoting greater visibility and understanding of SAF within airport operations and personnel

Disadvantages:
- SAF-specific fuel supply and airport infrastructure for receiving, storing and blending the fuel and a tank farm infrastructure adapted for this purpose is required
- Lack of available space and capacity necessary to cope with the expected increase in SAF use by 2050
- Efficient and transparent accounting system needed to track fuel deliveries to various airports
- Transportation restrictions: Transportation of 100% SAF through pipelines is currently not possible, so special trucks are required for SAF transportation
- Airport tanks are relatively small
- Certification of fuel is mandatory at the airport, which comes with challenges such as on-site blending regulations and lack of expertise on certification requirements
- Higher traffic congestion on the ground due to larger number of transport movements

2 | Mixing at a production site has the following advantages and disadvantages:

Advantages:
- Professional experience and expertise in handling various hydrocarbon products, including bio-based SAF
- Different transportation options

Disadvantages:
- Only suitable for large quantities of aviation fuels, as quality control is only profitable for large quantities
- Independent tank farm and separate pipelines required for Jet fuel A1, as it must not be pumped through the pipelines of a refinery
- Potentially long transport routes for SAF, resulting from the geographical separation between refineries and bio-based SAF production facilities
- Bio-based SAF storage at the production site must be made possible
- The need transportation to distribute the product (trucks, rail connections, etc.). For example, companies such as Neste, Altens and TRAPIL have joined forces in Europe to transport 3.5 million liters (2,800 tonnes) of bio-based SAF through a European pipeline (e.g., NATO pipeline) for the first time. Transport via the 192-kilometer pipeline reduced greenhouse gas emissions by 92% CO_2 equivalents compared with conventional tanker logistics. The pipeline runs between the port of Le Havre in north-western France and the town of Gennevilliers near Paris.[125]

5.2 Core infrastructure at airports

The fact that SAF mixed with J ET-A1 in accordance with standards is compatible with the existing infrastructure of airports means that some of the facilities can be used. At airports, the infrastructure for Bio- and E-SAF is therefore identical. The core infrastructure includes

- Logistics and transportation
- Storage and tank system

As already mentioned, blended aviation fuels can be transported by pipeline, truck, train or ship, or produced directly at the airport. Storage can take place either separately or together. Large quantities of bio-based SAF or its blends enriched up to 50% are often transported by train and small quantities by truck, as the production sites are usually remote. Conventional kerosene and generally SAF blends with up to 50% SAF are usually transported by pipeline. The decision for a transportation method depends on various factors such as costs, availability of infrastructure and environmental impact.

Different transportation options have advantages and disadvantages:[116]

- Transportation by truck is particularly suitable for smaller quantities of SAF, as it has a high degree of flexibility and reliability. Truck transport is practical and cost-effective, as it does not require any complex loading or unloading infrastructure. For larger volumes of SAF, however, additional transport infrastructure measures may be required, such as the construction of staging areas or the development of access roads, which incur additional costs. Furthermore, there are hurdles in the form of limits on unloading capacity and specific compatibility requirements on the part of the airports.

- Transportation by train allows larger quantities of aviation fuel to be moved. However, rail transportation requires an existing rail infrastructure that connects the SAF refineries with the blending stations. Investments may have to be made to develop rail routes before effective transportation can be guaranteed.

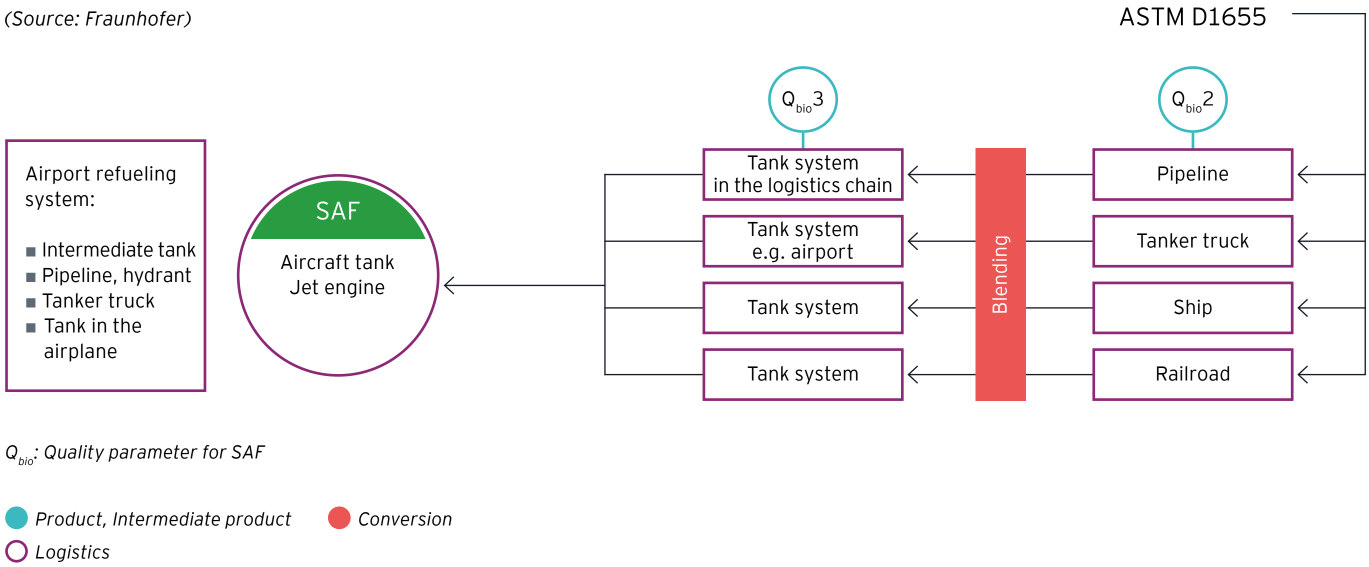
- Transportation by ship also makes it possible to move large quantities of aircraft fuel. However, the lack of port infrastructure near many airports can be a challenge. In addition, the development of new waterways requires extensive expansion. As a result, this mode of transportation is mainly suitable for refineries or terminals that already have access to water.

- Pipelines offer considerable potential due to their low operating costs and often already existing infrastructure at airports. However, the problem is that the transportation of pure SAF in multi-product pipelines is currently not permitted. As a result, the use of pipelines is only possible in some countries and is often only permitted for certified SAF. Another disadvantage is the high capital costs for building new infrastructure. Additionally, the need to integrate SAF into the existing pipeline sequence of other hydrocarbons is not economically viable, especially when SAF quantities are low.[116]

Figure 36

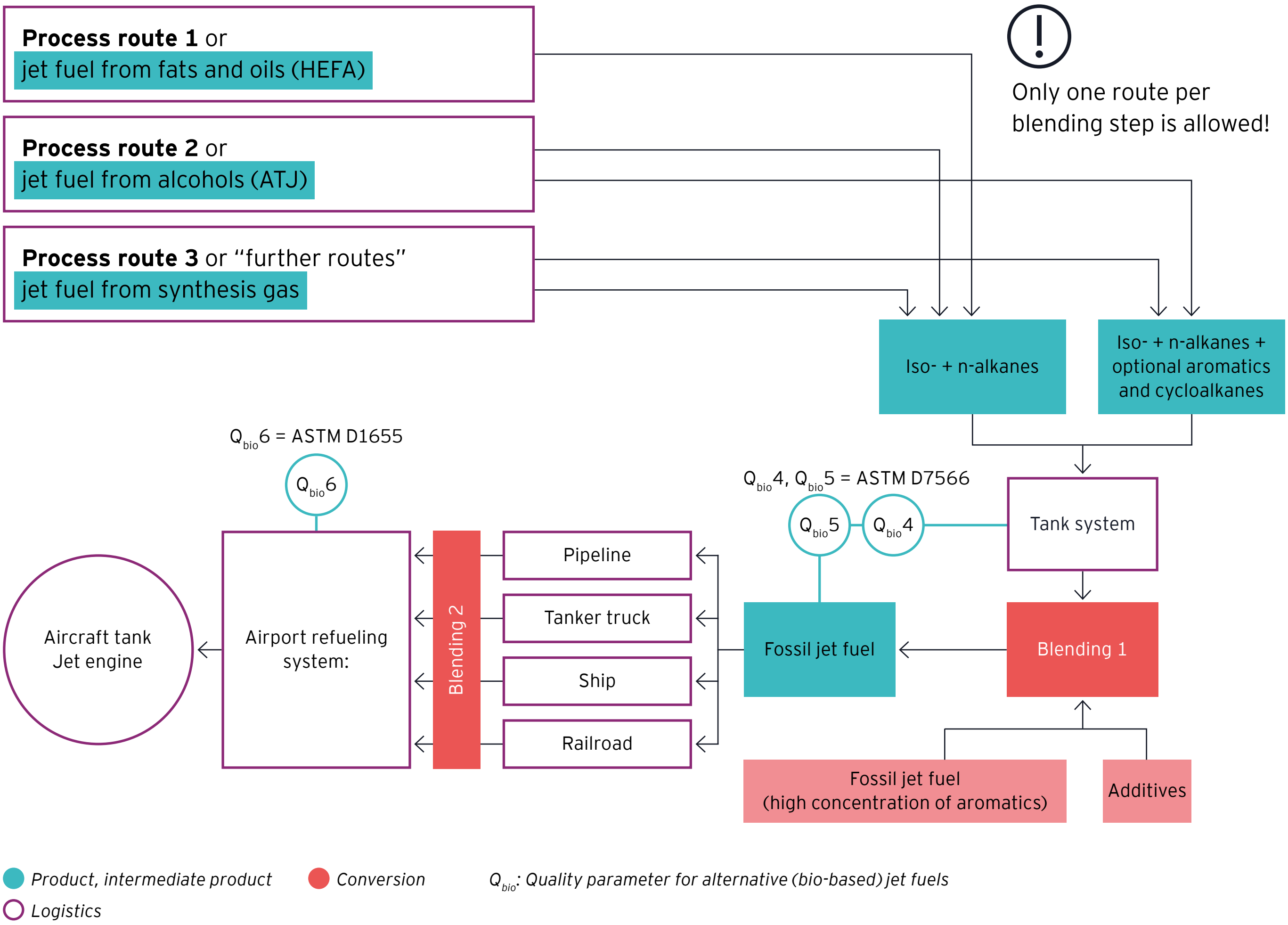
Overview of the general infrastructure for SAF blends and/or fossil jet fuel

(Source: Fraunhofer)



Q_{bio}: Quality parameter for SAF

Figure 37
Structure and route for SAF transportation
(Source: Fraunhofer)



"

The switch to H_2 as an aircraft propulsion system requires changes to the airport infrastructure. Until around 2040, supply by truck and trailer is feasible. After that, the increased demand will require the use of cryogenic and spherical tanks for storage.

Jan Eike Blohme-Hardegen, Head of the Environmental Department, Hamburg Airport

SAF blends can be transported via NATO and/or the Trans-European Transport Network (TEN-T) pipeline system, for example, which is currently used to transport kerosene.

Since 2023, it has been possible to transport SAF blends via the NATO pipeline, which normally supplies Brussels Airport with kerosene. The airport is the only airport fully supplied through this pipeline. For this project, Brussels Airlines purchased over 2 million liters (1,586 tonnes) of blended aviation fuel containing 38% SAF. In the long term, pipeline transport can enable a significant reduction in greenhouse gas emissions.[126, 127]

According to airport representatives, many European airports do not take responsibility for the infrastructure of fuel transportation. Therefore, they do not support the new regulation regarding SAF quantities at airports and emphasize that these problems should be included in the regulation and that the SAF supply chains should be improved instead. One example of this is the book-and-claim system.

In addition to transportation options, appropriate storage for SAF at airports should also be ensured. To this end, storage capacity in the EU must be increased, which can be achieved by building new fuel storage facilities.[53]

A first option for storage is the separate storage of SAF and conventional kerosene (Jet-A1). The two fuels are then mixed in a third tank before the mixed aviation fuel enters the aircraft. Due to the separate storage, the SAF quality assurance can be carried out more easily; however, the inventory management is challenging due to the different densities of the two fuels and the constant filling and emptying of the tank.

Storage in separate tanks and transport to the aircraft using refueling vehicles can lead to increased costs and complexity for airports without a separate infrastructure. However, this approach offers transparent delivery and precise control of the fuel quantities used.

An alternative method is to store SAF by mass balance in the same tanks as conventional kerosene. Since SAF is often delivered to airports in a blend of 30% to 45% with JET-A1, it is further diluted in these storage tanks before being used to refuel aircraft. This approach reduces the need for separate infrastructure and can reduce costs.[128]

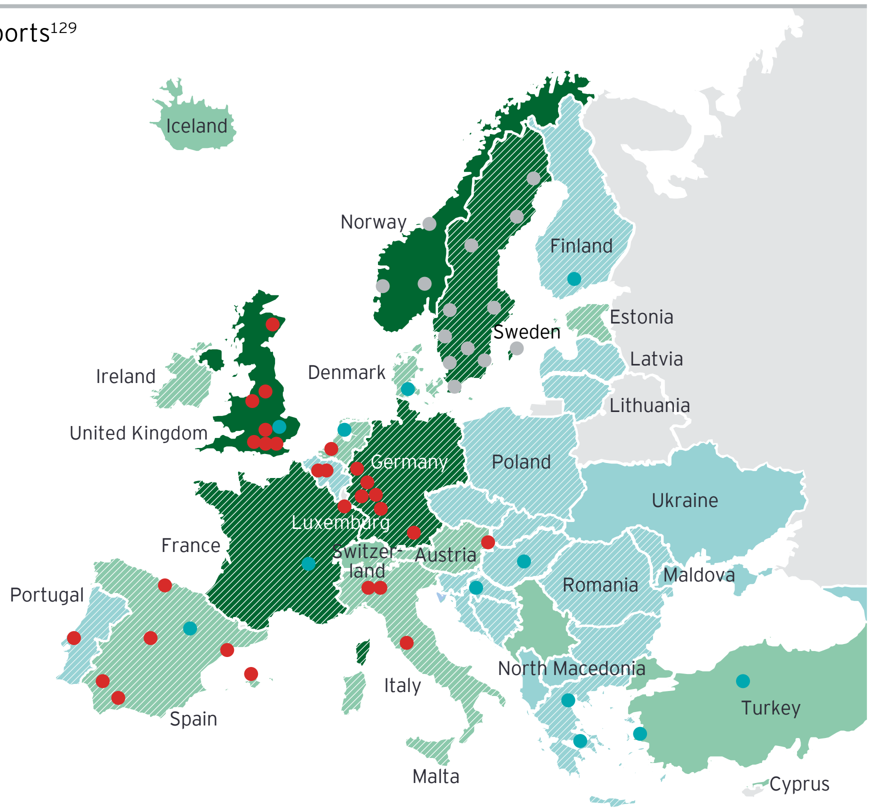
At present, airports are generally not equipped for blending fuels. Therefore, investments in equipment, qualified personnel and, if necessary, appropriate laboratory facilities for analysis and software would be required. In addition, insurance would be necessary and CoA (Certificate of Analysis) documents would have to be drawn up. One possible solution could be the construction of a new production facility (greenfield or brownfield site) near the airport. However, this would result in additional costs, as extensive tests would have to be carried out.

There are already several airports in Europe that provide SAF and the associated infrastructure. As the map below (Figure 38) shows, in Germany, for example, Hamburg, Frankfurt, Munich and Cologne-Bonn airports regularly offer refueling with SAF.

Figure 38

Overview of the use of SAF at European airports[129]

(as of February 2025)



SAF policy

- *EU SAF obligations*
- *National SAF roadmap under development*
- *National SAF measures*
- *Other*
- *Airports that offer SAF*
- *Depends on the airline's decision*
- *Airports with SAF regulations in force*

Financing and costs

6

> As SAF is at least twice as expensive as conventional jet fuel and accounts for 30% of an airline's costs, financing becomes a very relevant issue.

Air France-KLM Group

Introduction and summary of the chapter

The defossilization of the aviation industry depends on airlines being able to procure SAF in sufficient volumes. To achieve this, the supply of SAF must be increased many times over and available at competitive prices.

At the moment, the price of SAF is still around one-and-a-half to six times the price of conventional kerosene.[130] This is because some technologies are not efficient and raw materials relevant to bio-based SAF can be relatively expensive depending on the region. This is also reflected in our internal calculation model of the minimum sales price based on the levelized cost of bio-based SAF (LCO for Bio-SAF) for HEFA and E-SAF (LCO E-SAF) on the methanol route.

According to EY calculations, the minimum selling price for the bio-based SAF mixture consisting of Bio-SAF, Bio-HVO and Bio-Naphtha is approximately US$2,680/ton globally, and approximately US$4,880/ton for E-SAF. In general, either bio-based SAF or Bio-HVO is the more expensive product, depending on market demand and sales volume, while Bio-Naphtha is cheaper.

For comparison, the average global kerosene price in mid-July 2024 is around US$820/tonne.[131] Over time, however, the minimum selling price for E-SAF will fall due to technological advances and lower energy prices, making it more attractive than kerosene. Although the minimum selling price for bio-based SAF is currently the cheaper sustainable alternative, it will increase over time due to various factors such as possible resource shortages etc. and will even exceed the minimum selling price of E-SAF from the mid-2030s.

To enable the transformation of global aviation to net-zero emissions by 2050, global investments in SAF infrastructure expansion totaling US$1.00 trillion to US$1.45 trillion are required. This corresponds to 6% of annual investments in fossil fuels and gases.[67] According to IATA, around US$48 billion will have to be spent annually by 2050.

With sufficient financial resources, stable policies, and regulations, the necessary framework can be established to manage current and future technological innovations as well as the expansion of production capacities.

Corresponding funding can come from private and public sources. Typical investment structures include public-private partnerships, CO_2 compensation programs, innovative financing models such as green loans, sustainability loans and venture capital, which is particularly required for high-risk projects and phases. Numerous public subsidies are available worldwide, which can also be used to finance SAF initiatives. The geographical distribution of these funding programs varies, with relevant funding sources in Europe, North America and some APAC regions, in particular. Nevertheless, additional government funding is required to enable the future scaling of SAF.

As the SAF market continues to develop, private investment is becoming increasingly important. Currently, private investment in SAF projects is on the rise worldwide due to growing interest and the increase in global SAF frameworks. Typical private financing instruments include bank loans and bonds, including green bonds.

Appropriate bankability and scalability of SAF projects are crucial for their successful financing. Bankability depends on the economic viability of the project, the efficiency and reliability of the technology, the availability and volatility of raw materials, government funding, subsidies and the legal framework. In addition, fixed purchase agreements to minimize the sales risk, the consideration of sustainability factors, risk minimization strategies and a competent team are important aspects for successful bankability. The scalability of SAF initiatives — the ability of a project to expand its capacities — is based on factors such as technology, profitability, infrastructure, regulation and sustainability.

The requirements for the current and future minimum sale prices for bio- and E-SAF, as well as for increasing scalability and technological maturity, include factors such as investors' willingness to invest in SAF projects and the bankability of the projects.

This chapter is initially dedicated to the basics and the associated challenges and necessities for the financing of SAF projects. It provides a detailed analysis of various financing instruments that are important for the realization of these projects. In addition, the chapter provides a comprehensive overview of the projected price development of Bio- and E-SAF for the global area and the APAC, EU and US regions for 2024 to 2050, based on well-founded internal calculations.

6.1 Development of the SAF cost structure and sales prices

To calculate the market price for bio-based SAF and E-SAF, we took the following financial ratios into account in the internal calculations:

- CapEx
- Production capacity and raw material supply
- OpEx
- LCoH

This information is also important for potential investors who want to invest in organic and E-SAF plants.

LCoH is used to calculate the costs per E-SAF or Bio- SAF unit produced over the entire lifetime of the production plant:

$$\textbf{Levelized Cost} = \frac{\sum_{t=1}^{N} \frac{(CAPEX_t + OPEX_t + Interests_t)}{(1+r)^t}}{\sum_{t=1}^{N} \frac{(Production\ in\ units_t)}{(1+r)^t}}$$

r = weighted average cost of capital
t = time
N = Service life of the production system

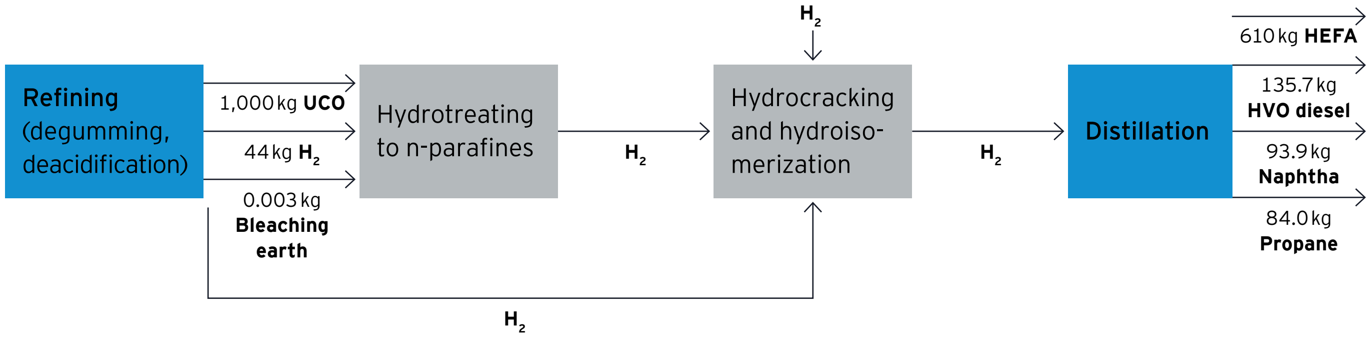
Under LCoH calculations of E-SAF and Bio-SAF, time trends (2024, 2030, 2040 and 2050) and regional differences in the EU, USA and the APAC region were also considered. To enable producers to make a reasonable profit, which is necessary for reinvestment, risk hedging and maintaining competitiveness, a profit margin of 5% was added to the respective life cycle cost (LCO) for both SAFs, which sets the minimum selling price.

The LCO for bio-based SAF was calculated based on the HEFA route (process route 1), as this process route is the most mature to date.

Figure 39

HEFA route considered for the LCO and price calculations

(Source: EY, MVaK[132])



In this case, the HEFA-based SAF under consideration is a premium product and is produced exclusively with green steam (from biomethane) during the manufacturing process.

Detailed assumptions are explained in Appendix II.

The LCO for E-SAF was calculated based on the methanol route. A premium product is also considered here.

Figure 40

LCO for bio-based SAF (LCO for Bio-SAF) incl. profit margin in US$/kg

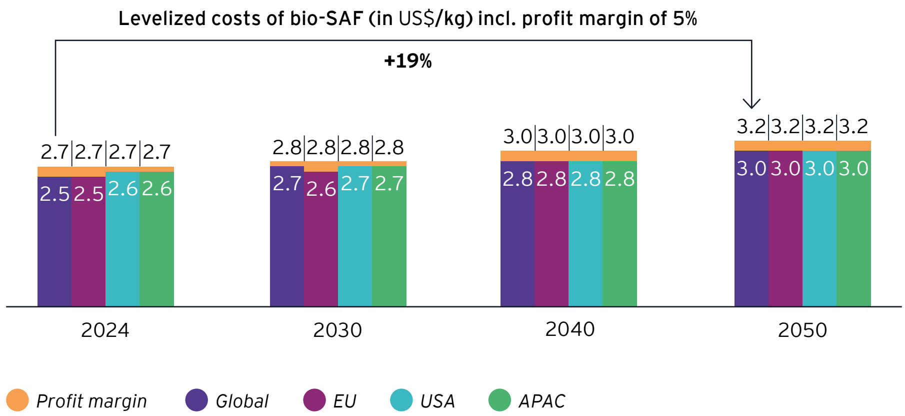
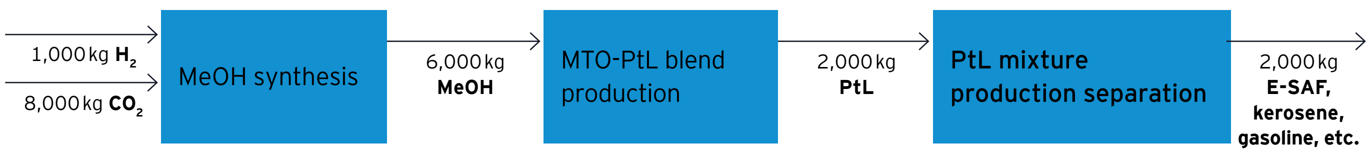


Figure 41

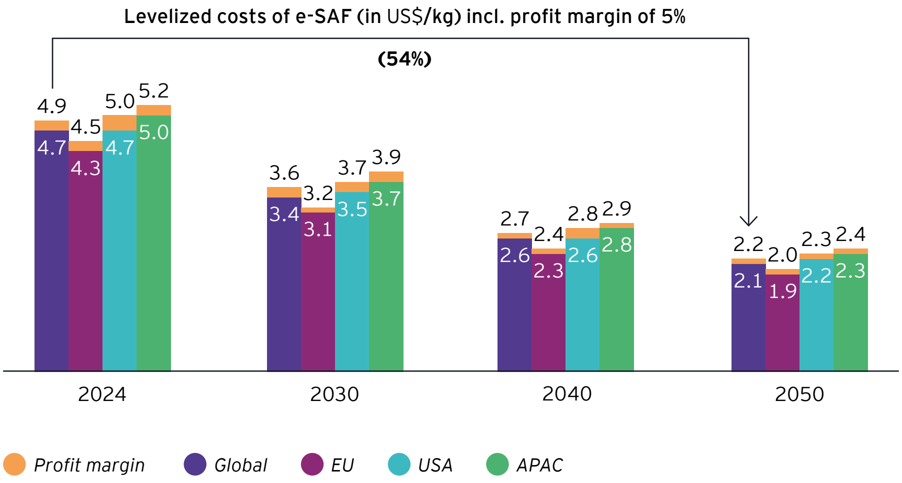
Methanol route considered for the LCO and price calculations

(Source: EY)



calculation

Figure 42
LCO of E-SAF including profit margin in US$/kg



As can be seen in Figures 40 and 42, according to our calculations, the LCO for bio-based SAF (in each case without profit margin) is currently around US$2.5/kilogram (~US$2,550/tonne) globally and those for E-SAF are around 80% higher at US$4.7/kg (~US$4,650/tonne).

In the European Union, the LCO for bio-based SAF in 2024 will be as follows due to lower energy prices in Europe to US$2.5/kg (~US$2,530/tonne) and those for E-SAF to US$4.3/kg (~US$4,360/tonne).

Prices in the United States and the APAC region are significantly higher than in the EU due to higher energy costs. Specifically, the costs for bio-based SAF in both regions are US$2.60/kg (~US$2,560 per tonne). For E-SAF, the costs are US$4.70 per kilogram (US$4,730 per tonne) in the USA and US$5.00 per kilogram (US$4,970 per tonne) in the APAC region.

Overall, the current costs for bio-based SAF are, therefore, significantly lower than for E-SAF, regardless of the region.

This is primarily due to the higher technological maturity and scalability of HEFA production compared to e-SAF. For years, commercial HVO diesel plants have been operating globally, with HEFA consistently produced as a byproduct. Facilities dedicated to HEFA-SAF largely rely on the same processes and infrastructure as those used in HVO diesel production. The main difference between these types of facilities lies in the quantities and types of raw materials used. Currently, bio-based SAF is significantly more attractive to investors due to the low production costs. However, this situation may change over time.

The increasing technological development and scaling of E-SAF is leading to falling production costs for E-SAF and lower capex on corresponding production facilities in all regions, as can also be seen in Fig. 42.

The expected technological progress and the resulting lower prices to produce green hydrogen will also lead to a decline in the LCO for E-SAF.

Falling costs for renewable energies also have a significant impact on the overall falling LCO for E-SAF due to the comparatively high energy requirements in the production of E-SAF.

> “At present, the relative production costs of PtL-SAF are still significantly higher than those of biogenic SAF. Nevertheless, PtL-SAF offers great long-term potential to significantly reduce the climate impact of air traffic.

Melanie Form, Member of the Management Board and Managing Director, Aireg

The LCO for bio-based SAF is developing in the opposite direction, increasing due to potential resource constraints. Restrictions on usable biomass and rising raw material prices stem from various challenges. These include natural disasters, crop failures, land use conflicts, and increased demand from industries such as food production, shipping and chemicals. Regulatory requirements (see Chapter 2) and the increasing awareness of climate protection, coupled with the lack of sustainable alternatives that are similar in price to the bio-based SAF produced via the HEFA route, are also leading to rising LCOs for Bio-SAF.

Compared to other process routes, it is expected that the demand for SAF from HEFA and the LCO for bio-based SAF will rise more sharply, as the production of HEFA also generates HVO diesel, propane, and naphtha as by-products. These by-products can generate additional profits in already established markets (e.g., biodiesel, chemicals, lubricants, etc.), thus increasing the bankability of the projects.

In 2050, the global LCO for bio-based SAF is US$3.0/kg (~US$3,330/tonne) and that for E- SAF is around 30% lower at around US$2.1/kg (~US$2,140/ tonne) (see Figures 40).

These developments suggest that the LCO for bio-based SAF and E-SAF will converge globally around 2038, as is projected for the USA. In the EU, this alignment is expected as early as 2035, while in the APAC region it is anticipated around 2040. Beyond this point, the LCO of bio-based SAF is projected to exceed that of E-SAF across all regions.

> “
> It is to be expected that the willingness to purchase biomass-based SAF in logistics and companies will remain, even with rising prices, as their goal is to reduce Scope 3 emissions. In contrast, passengers are price-sensitive, which is partly due to a lack of information about SAF. Airlines are therefore faced with the challenge of being able to pass on price increases to customers with difficulty.
>
> **Bernhard Dietrich,** Head of CENA Hessen, Hessen Trade & Invest GmbH

In the year 2050, the LCO for bio-based SAF globally will be US$3,0 per kilogram (~US$3,330/tonne) and those for E-SAF were approximately 30% lower at approximately US$2,1 per kilogram (~US$2,140/tonne) (see Figures 40 and 42).

In the European Union, the LCO for bio-based SAF will also rise to around US$3.0/kg in 2050 (~US$3,020/ tonne) and those for LCO E-SAF, again, due to lower energy prices in Europe, to only US$1.9/kg (~US$1,890/tonne).

Similar trends can be seen in the USA and the APAC region in 2050 (see Figures 40 and 42).

Overall, the LCO for bio-based SAF will increase by about 19% between 2024 and 2050, while the LCO for E-SAF will decrease by 53–56% over the same period.

Depending on the region, bio-based SAF is more interesting for investors and clients until around the middle or end of the 2030s, after which, based on our calculations and assumptions, investments in E-SAF plants are likely to be preferred.

6.2 Sources of financing

In order to provide the targeted quantities of SAF by 2050, an investment sum of US$1.00 trillion to US$1.45 trillion will be required. According to the Air Transport Action Group (ATAG), the annual financial requirement amounts to around US$48 billion.[133] By comparison, annual expenditure on natural gas and oil currently stands at US$420 billion.[134] The availability of financial resources at a global level plays a decisive role. While these are generally limited in the public sector, the private sector could potentially provide considerable sums. According to estimates by the Financial Stability Board, the global private institutional sector currently has assets of around US$225 trillion, a sum that could more than double by 2050. Such an increase in available funds, if increasingly financed in SAF, could lead to a significant acceleration in the production and use of SAF, including infrastructure development.[67]

Typical investment structures for financing SAF projects are:

1 | Public-private partnerships based on cooperative investment activities by governments, industry stakeholders and financial institutions. This type of financing combines public funds and private expertise. This allows the risk that arises during SAF scaling to be spread and financial resources to be pooled to implement larger projects.

2 | Furthermore, aviation companies are also increasingly turning to CO_2 compensation programs to finance SAF projects. These enable companies to offset their CO_2 footprint.

3 | The use of Innovative financing models, including green bonds and sustainability loans, offer the decisive advantage that they are available on preferential terms if certain environmental performance criteria are met.

4 | Ultimately, through Venture capital and impact investors are driving additional funding as they invest in both targeted and innovative and potentially risky projects that are avoided by traditional funding sources.[135]

When setting up initial SAF projects, both equity and debt capital are generally used, although the ratio can vary depending on the project phase. While the financing costs for an initial project tend to be higher due to the higher risks, it is likely that they will fall for subsequent projects. Both private and public financing instruments are used for the development of SAF projects. Public funding is essential, especially in the initial phase. As the SAF market matures, private investment becomes more important. Private capital is particularly easier to mobilize when projects generate sufficient income to meet existing obligations and generate an attractive return on investment.[136]

Private investments in the SAF sector are increasing worldwide due to the growing interest in SAF and the support of the market through global political frameworks.

“

The high costs are currently still preventing progress with new technologies — particularly around PtL. Targeted support would be necessary to solve this problem: For the first installations, this must be a combination of CapEx and OpEx support to avoid a first-mover disadvantage — for both producers and airlines.

Henrik von Storch, Director Global Sustainable Aviation Fuels, DHL Express

According to the ICAO, typical private financing instruments include bank loans and bonds, including green bonds. Bank loans play an important role in the financing of SAF projects but entail the risk that borrowers could become insolvent if the risk exposure is too high. Loans are repaid as part of the operating costs, including interest, over a long period. An additional challenge is the frequent lack of credit ratings for projects, especially in developing countries. This can lead either to a reluctance on the part of banks to provide financing or to higher interest demands to hedge against the risk of non-payment. On the other hand, securities offer a long-term financing option that is adjusted to the expected cash flow of the project. They are tradable and thus provide further opportunities for investment and returns.[137]

The following benefits can be achieved with private investments in SAF:

- SAF portfolios can help institutional investors advance their green energy goals and contribute to the transition toward a net-zero economy. In addition, SAF investments offer geographic diversification opportunities, particularly in regions where investors have had limited exposure to other asset classes.
- SAF projects increasingly offer attractive risk/return ratios and steady cash flows, which are favored by the private institutional sector. The reason for this development is the improvement in the regulatory and political environment by national governments, the adoption of measures to reduce excessive risk by the public sector and the growth of the SAF market.
- SAF can serve as a valuable asset class by helping to stabilize overall portfolio returns. As SAF investment performance tends to be uncorrelated with equities and bonds, it can reduce overall portfolio volatility and enhance diversification.
- Global investments in SAF offer future security, particularly regarding the introduction of nature-based financial instruments such as the Global Biodiversity Framework and the Taskforce on Nature-based Financial Disclosures (TNFD). The integration of such mechanisms into the field of environmentally friendly investments makes effective regenerative and restorative SAF initiatives increasingly attractive as long-term, future-proof and bankable investment opportunities.
- State engagement in SAF offers interesting opportunities for cooperation and long-term potential for investors. With regard to investments in developing countries, there is also the option of co-investments with state actors such as national development banks, but also multinational development banks such as the World Bank, which could enable obtaining financial resources at more favorable options compared with the private capital market.[133]

As already mentioned, public funding plays a decisive role for both investors and producers and has a significant influence on market development. Government funding can also enable the scaling of global SAF production, especially in the financing of technology developments. Public sector funds minimize the risks of private investment by increasing capacity in technology and operations, supporting high-risk and high-cost pre-financing, subsidizing higher borrowing costs and driving the development of regulatory programs.[137] Europe and North America, in particular, have many financing projects with numerous funding programs that promote the development of both bio-based SAF and E-SAF. We were also able to identify a significant number of funding initiatives in selected countries in the APAC region that focus on supporting SAF. In contrast, only a limited number of funding programs are in Latin America.

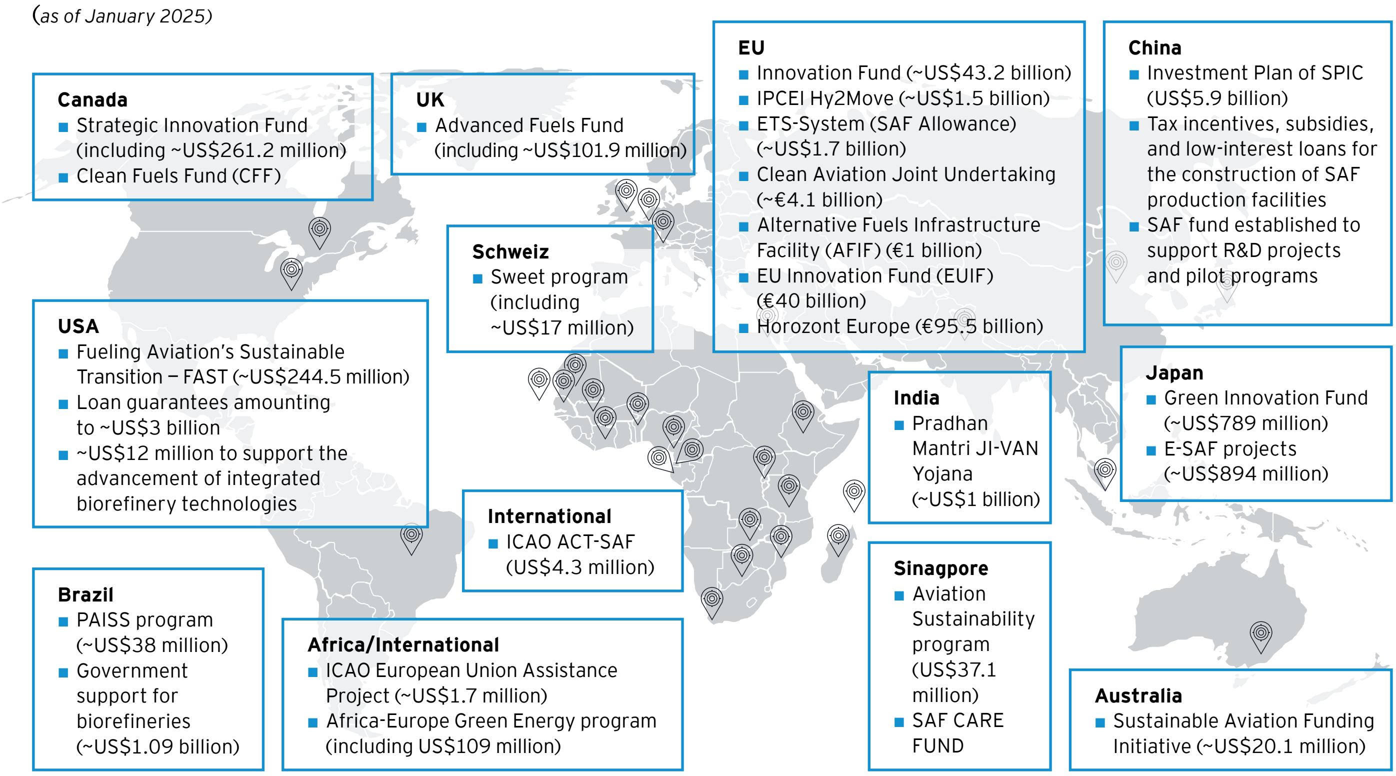
The least project funding activity is in Africa, where there are mainly international programs (e.g., ICAO European Union Assistance Program, ICAO Act SAF) that are specifically aimed at promoting SAF projects on the continent. The development of biofuels and bio-based raw materials in Africa is largely dependent on financial support from foreign governments, development banks and state-owned enterprises.[138]

The regions shown in Figure 43 can be one of the attractive locations where subsidies are available or have been awarded. Existing government funding programs are also presented. The selected projects support the expansion of SAF, and of E-Fuels and biofuels. Although funding programs that focus exclusively on H_2 are not listed here, they can still make a significant contribution to the promotion of E-SAF. It should be noted that the map only shows a selection of funding programs and does not provide a complete picture.

Support for E-SAF is being provided. It should be noted that the map only represents a selection of funding programs and does not provide a complete overview.

Figure 43

A selection of global government support projects for SAF, E-Fuels and biofuels[i, j]
(*as of January 2025*)



Annex I provides a detailed overview of the global public funding initiatives for SAF.

i It must be emphasized that the projects mentioned in this context are only a selection of representative initiatives. It should also be noted that the transparency and visibility of funding initiatives may be lower in some regions than in others.

j The conversion from euros to US dollars is based on our EY pricing model. The conversion of country-specific currencies is carried out on the basis of the exchange rates at the time of publication of the projects.

6.3 Bankability and scalability projects of SAF

Bankability and scalability are decisive factors for the successful financing and implementation of SAF projects.

The bankability of a project is characterized by its ability to meet the criteria of security and profitability for financing by credit institutions. For SAF projects that fall under the category of renewable projects, project readiness and full planning must be in place to qualify the project for financial negotiations. In addition, the project contributes to building investor confidence through acceptance contracts and solid financial modeling. SAF projects should have an experienced team with expertise and a track record of success. Furthermore, projects must have a comprehensive risk analysis that considers both project- and country-specific risks. They should be compatible with overarching frameworks such as the SDGs, ESG regulations and country-specific priorities. These non-financial factors are important for investors.[139]

In this subchapter, the focus is on financial support for start-ups and companies in the early stages. Funding through venture capital investments is based on the current market situation in the aviation industry, which is characterized by new technological developments, regulatory adjustments and changing consumer preferences.

Scalability refers to the ability of a project to efficiently expand its capacities to meet the growing demand for SAF required in the future. It is critical to achieving future SAF objectives and the decarbonization of the aviation sector. To assess the scalability of E- and Bio-SAF, this chapter examines the five dimensions of technology, economics, infrastructure, regulation and sustainability. It is important to note that the factors for bio-based SAF and E-SAF differ, which necessitates a differentiated analysis.

“

We see the financial challenge in a significantly increasing cost base, which will require an adjustment of the airlines’ business models. From an operational perspective, we expect fewer difficulties. An engine upgrade may be necessary to enable higher SAF blends.

Air France-KLM Group

6.3.1 Bankability

Sufficient bankability shows that a project can lead to tangible results and profitability and is therefore crucial for securing the necessary financial support.[139] The bankability of SAF projects depends on various factors that investors and lenders take into account to assess the risk and profitability of these. Here are some key factors:

- The economic viability of the project. This includes a solid cost-benefit analysis, competitiveness compared with conventional fuels and potential sources of revenue such as CO_2 certificates.
- A mature technology to produce SAF. The technology must be reliable and proven.
- The availability and fluctuations of raw materials. The price volatility of raw materials can affect the economy.
- Government funding, subsidies or legal framework conditions. These can favor the use of SAF and significantly improve bankability.
- Fixed purchase agreements with airlines or other customers. This is about securing stable income and minimizing the sales risk.
- Compliance with environmental and social standards. Projects such as these are more attractive to investors who value sustainability.
- An experienced and competent team. This increases investor confidence.
- The availability of strategies to minimize and manage risks, including technical, financial and market-related risks.

Investments for SAF scaling can be made in the initial phase of the projects through venture capital and in later phases of industrial scaling on a large scale through debt capital from the banking sector, capital from the private equity sector or through the public capital market as part of an initial public offering (IPO). Sufficient banking capacity is essential to enable these investments and to successfully drive forward the implementation of SAF projects.

Venture capital investments are one of the central forms of financing for start-ups, companies in the early stages of development and up-and-coming companies with high growth potential. This capital is typically provided by private equity investors.[140]

In the aviation sector, venture capital enables the provision of financial resources for innovative ideas and technologies, including SAF projects. Due to the inherent risks of SAF projects and new technological developments, venture capital plays a crucial role in financing. Investors evaluate factors such as market demand, competition and scalability before investing venture capital to minimize risks and maximize returns. Collaboration plays a central role in the venture capital sector of the aviation industry. Investors often seek strategic partnerships with industry experts, aviation companies and research institutions. This promotes access to expertise and resources and increases the chances of success for the companies financed.[141]

An analysis of past transactions shows that, in addition to financial investors, airlines also play an important role in the financing of start-ups in the SAF sector. One example of such transactions is the investment of 30 million US dollars by Southwest Airlines in February 2024 in the start-up LanzaJet, the SAF division of LanzaTech.[142] United Airlines also participated with its Corporate Venture Capital Fund in a financing round of US$22 to support the start-up OXCCU in 2023. Founded by scientists and technologists from Oxford University, this company is planning to develop and launch a new technology for the production of SAF from CO_2.[143] Another example is the participation of Wizz Airlines and two other airlines in a financing round of Clean Joule, a start-up specializing in Bio-SAF, for US$50 million in 2023.[144]

United Airlines has set up a corporate venture capital fund, the Sustainable Flight Fund. The airline and its corporate partners have raised US$200 million, with an additional US$450,000 from clients. The fund supports start-ups that specialize in SAF research, production and technology.[145]

From 2010 to 2021, there were two phases of venture capital investments in Bio-SAF. Within the first five years, many companies succeeded in attracting venture capital on a large scale, especially to produce biofuels from algae, sometimes with bio-based SAF as a possible end product. However, large-scale production and competitive prices failed to materialize, and many companies went bankrupt.

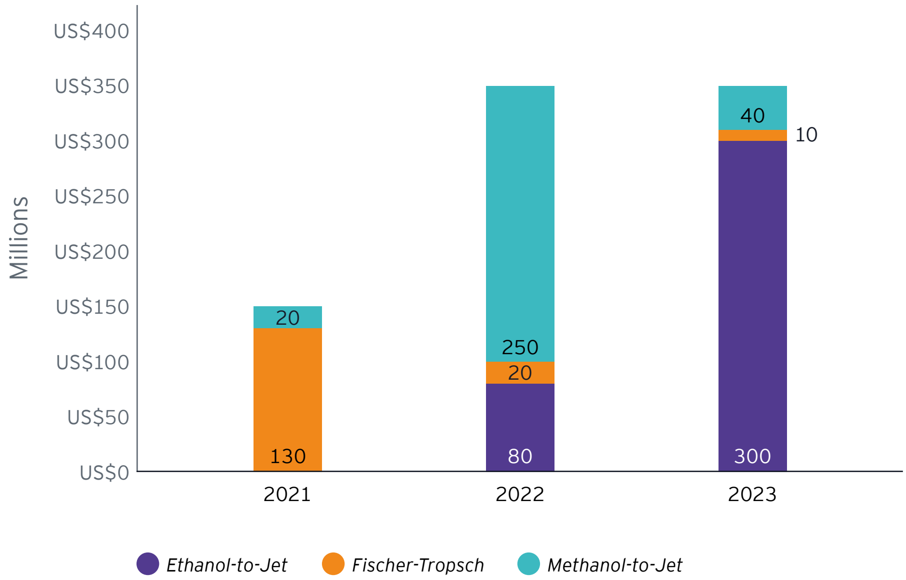
An increase in the average volume of funding for start-ups specializing in bio-based SAF was then recorded in the second phase from 2016 to 2021. In 2021, approximately US$1,800 million was invested in bio-based SAF start-ups worldwide, compared with only US$700 million in 2015 (see Fig. 57).[146]

This development in transaction volume indicates an increase in the valuations of similar start-ups over time and a higher number of late-stage start-ups that have been able to raise additional funding through venture capital to scale their production processes. Venture capital investments, differentiated according to SAF production routes, show a significant increase in investments in ethanol-to-jet projects. These recorded an increase of around US$80 million in 2022 to almost US$300 million in 2023. In contrast, the FT and methanol-to-jet production routes are characterized by a decrease in venture capital activity (see Figure 42).[147]

Figure 44

Venture capital investments in SAF production pathways (2021–2023)[147]

(as of April 2024)



According to Bloomberg, the global financing volume of climate tech companies provided in the form of venture capital and private equity amounted to US$51 billion in 2023. This corresponds to a 12% decline in financing activities compared with the previous year. The financing volume for climate tech start-ups shows clear crisis resilience in terms of financing activities, in contrast to the total financing volume across all sectors, which fell by a total of 27% over the same period. The largest share of total financing in the climate tech environment is attributable to companies that focus on business models to reduce emissions in the energy and transportation sector. Despite the only marginal decline in funding volume through venture capital in the climate tech sector, difficulties arise from the decrease in traditional IPOs.

Start-ups are trying to avoid potential undervaluations of their shares through IPOs. The reduction in exit prospects, particularly in the form of IPOs, proves problematic for investors who face difficulties when exiting their investments. If interest rates remain high in the long term, investors may struggle to achieve profits and successfully exit their portfolios. Battery manufacturers Northvolt and Envision AESC, as well as the energy provider Redaptive, have conducted large investment rounds in the past with the expectation of future IPOs.[148]

When it comes to raising corporate venture capital, start-ups can continue to take advantage of the fact that numerous industries are working on decarbonizing their business models. This is evident when examining the venture capital activities of these companies. For instance, AccelorMittal and BASF provided capital to LanzaTech as part of a financing round with a cumulative volume of €115 million (~US$120.75 million).[149] There are also signs of efforts on the part of conventional kerosene producers to invest in SAF. Shell, for example, has invested in LanzaTech alongside other energy companies.[150]

To expand its sustainable fuels business, Shell acquired the established Indonesian provider of sustainable fuels, EcoOils, in 2022, which produces corresponding aviation fuels from waste oils using the HEFA process.[151] In Germany, the start-up INERATEC received financing of US$129 million from various venture capital funds in 2024, partly from the corporate venture capital funds of Safran, Engie and Samsung.

INERATEC manufactures reactors for the synthesis of liquid fuels (so-called synfuels) from non-fossil raw materials. Its patented technology and proprietary production process are designed to enable high scalability and efficiency.[152, 153]

All these partnerships, investments and acquisitions in recent years have contributed to the creation of an active venture capital market. This is essential for the development of early-stage SAF projects and for start-ups in the SAF sector.[154]

Bank lending plays a central role in SAF production capacities, as debt financing is significantly more favorable than equity investments. In contrast to research and development funding, banks are willing to provide loans for production facilities, as technological risks in the production process are significantly lower and there is also the option of utilizing the production facility.[155]

One challenge, however, is that banks are reluctant to lend if the risk is too high. As they generally have less experience with SAF projects, they have to rely on credit ratings to assess the credit risk. This information may not be to a sufficient extent for projects in the SAF sector. Public institutions such as governments and multinational development banks may be able to assess some of this risk upfront, thereby protecting banks from risk and keeping interest rates low.[136]

As the HEFA technology does not present any technological risks in terms of scaling, the expansion of the corresponding production capacity can be financed by borrowed capital from banks. With future technological developments, an expansion of financing activities to other SAF production processes can also be expected. Nevertheless, banks also play a decisive role in the development of technologies that are not yet sufficiently technologically mature to be financed by banks: they can act as intermediaries between potential investors and companies.[155]

One commercial bank with diverse activities in SAF projects is Bank of America, which is financing the production and use of 3.8 billion liters (3 million tonnes) of SAF by 2030 by mobilizing US$2 billion.[156]

In February 2024, Cathay United Bank Singapore signed a Green Trade Loan with the company Apeiron, which specializes in the procurement of UCO for the production of SAF.[157]

Canada Infrastructure Bank is also investing US$8.4 million in the company Azure, which plans to start SAF production by 2027. This is an example of support for a SAF project in the FEED.[158]

Financing activities by development banks are crucial in order to promote the expansion of SAF projects, particularly in developing countries. With the Green Climate Fund, the world's largest climate fund, the Asian Development Bank supports developing countries in implementing their nationally determined contribution targets. In the period from 2020 to 2023, the fund mobilized US$10 billion in over 100 countries.[159]

IPO activities are another way of raising additional capital. In addition to raising capital, public capital markets enable increased visibility and credibility of the company, which in turn increases market presence. An IPO also enables an exit option for investors and thus the mobilization of capital for new projects.

Publicly traded SAF options may become more important in the future. In the past, companies such as Gevo and LanzaTech have made use of this financing option. LanzaTech successfully completed its IPO in 2022 by means of a SPAC (special purpose acquisition company) construction. In the process, the company raised around US$275 million at a valuation of around US$2.2 billion. This amount is made up of an investment of US$125 million by various investors, including BASF and ArcelorMittal, as well as US$150 million generated by the acquisition vehicle through its IPO.[160]

However, the share prices of non-established companies such as Gevo and LanzaTech are showing a clearly negative trend (see Figure 43). In the case of Gevo, this development is mainly the result of delays in the expansion of production and the limited informative value of the currently still low revenues for forecasts on future business development.[161] Meanwhile, LanzaJet opened the world's first ATJ-SAF production plant in the USA in January 2024. The plant is expected to produce up to 10 million gallons of SAF and sustainable diesel per year.[162]

Another example is NEXT Renewable Fuels Inc. which, despite a failed IPO, is planning another IPO in 2023. The reason for the failure of the previously planned IPO with a SPAC was the downturn in the SPAC market.[163]

Neste is experiencing a negative trend in its stock price, which can primarily be attributed to the profit margins reported in February 2024, which are significantly lower than expected. For 2024, the company expects a sales volume of 4.4 million tonnes of sustainable fuels, with sales expected to generate a margin of US$600 to US$800 per ton. The targeted margin for 2024 is significantly below that of the previous year, which was US$863 per tonne. This due to a significant increase in competition and a reduction in tax benefits for the use of sustainable fuels. Neste plans to convert all existing refineries into plants for the production of sustainable fuels by the mid-2030s.[164]

Figure 45

Share price performance of selected companies in SAF production

(as of April 2024)

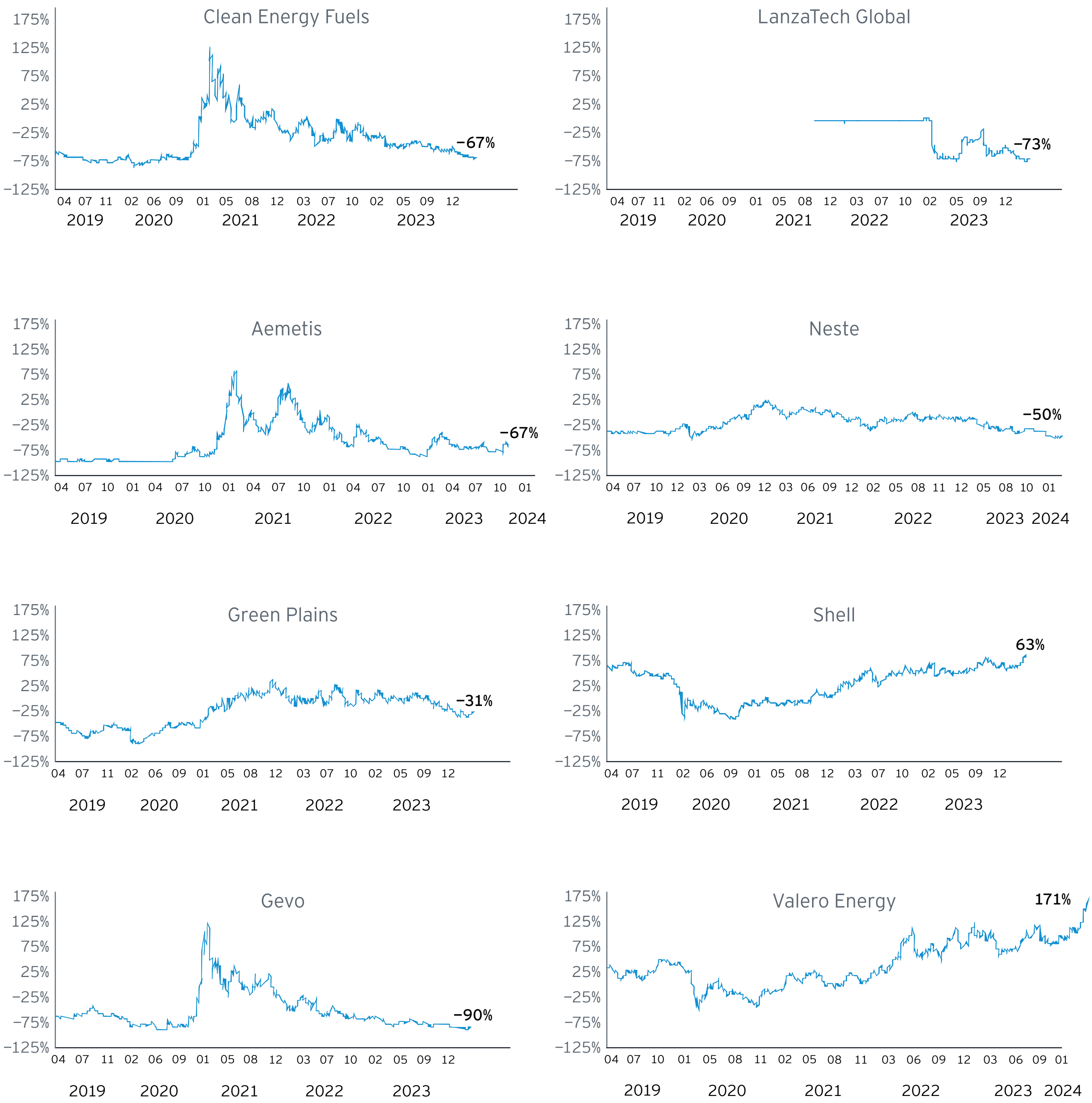


Table 11

Selected key financial figures in US$ million for SAF[165]

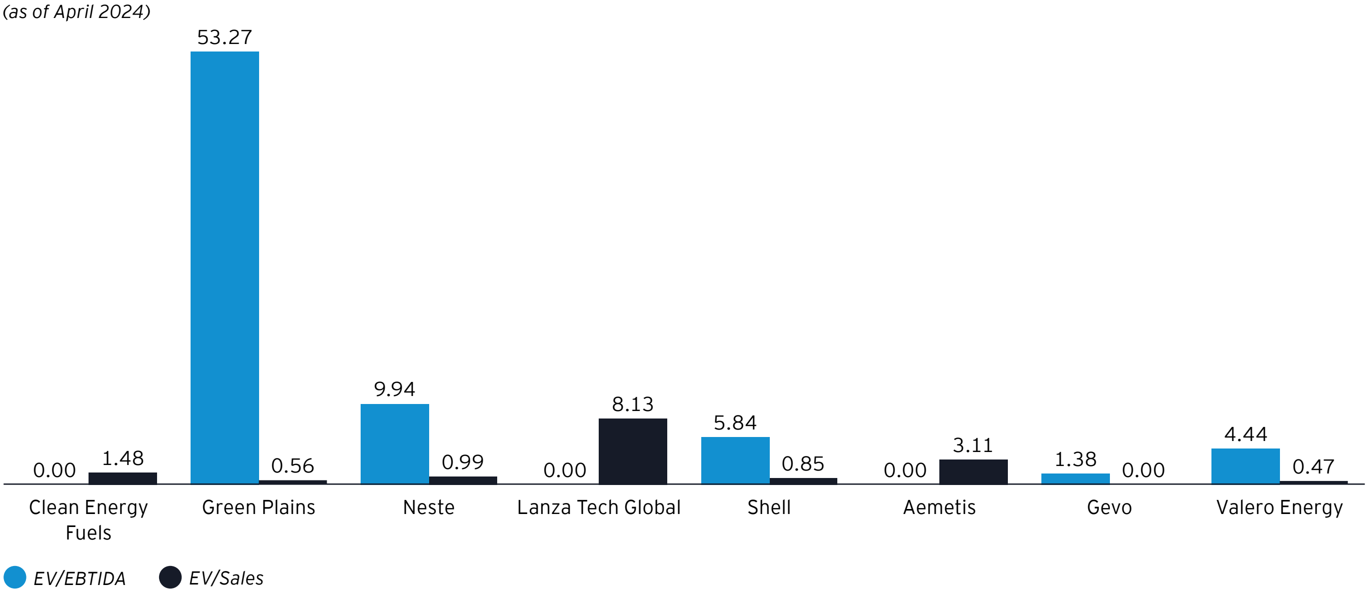
(as of April 2024)

	Revenue*	EBITDA*	Net income*	Market capitalization**	Total enterprise value**
Shell	254,623	37,168	15,568	181,652	214,696
Valero Energy	139,001	14,659	8,835	54,651	63,398
Neste	22,926	2,286	1,433	17,277	20,251
Green Plains	3,296	35	(93)	1,303	1,779
Clean Energy Fuels	425	(33)	(100)	538	656
Aemetis	187	(30)	(46)	183	610
Lanza Tech Global	63	(98)	(134)	485	412
Gevo	17	(63)	(66)	151	(49)

Figure 46

Goodwill (EV)/EBITDA and EV/Sales – multiples for the fiscal year ending December 31, 2023 (12 months)[165]

(as of April 2024)



Private equity financing is playing an increasingly important role as the SAF production process becomes more established. A significant increase in the involvement of private equity investors in the financing of SAF producers is to be expected.

An example of a private equity investment in the SAF sector is Macquarie's participation in SkyNRG in 2023, where €175 million (~US$189 million) was invested. SkyNRG plans to build an SAF production facility in Europe and the USA by 2030 in cooperation with various partners such as KLM and Boeing. The company has already concluded long-term supply contracts with a total volume of €4 billion (~US$4.32 billion). It was founded 14 years ago and produced SAF for the first SAF-powered flight in 2011.

This underscores the lengthy development processes that start-ups in the SAF sector face, as well as the importance of significant commercial successes to attract private equity investors. Macquarie has previously made investments in emerging, innovative technologies in the green sector.

* *Period fiscal year until December 31, 2023 (12 months)*
** *approximate period April to May 2024*

This illustrates the central importance of private equity investors specializing in investments in the energy and infrastructure environment for meeting future investment needs. SkyNRG has also developed the "Fly on SAF" platform, which enables passengers to offset the CO_2 emissions of their flight by purchasing a correspondingly calculated amount of SAF.[166]

> Current challenges in SAF production include technological difficulties, financing issues and compliance with the criteria set by the EU.
>
> **Bernhard Dietrich,** Head of CENA Hessen, Hessen Trade & Invest GmbH

In addition, a private equity financing of Velocys by growth investors such as Carbon Direct Capital, Lightrock, GenZero and Kibo Investments in the amount of US$40 million was announced in 2024. Velocys is a company that has been developing SAF technologies for 20 years, providing SAF manufacturing technologies to its clients.[167] These investments are intended to accelerate the delivery of Velocys technologies to client projects, expand the company's technology leadership position, scale production capacity and expand the expertise of the Velocys team.[168]

At the same time sovereign wealth funds represent an interesting source of financing for companies in the SAF environment, although the number of transactions is not yet significant. In summary, the bankability of SAF projects depends largely on the ability to bring together like-minded investors with a strong engagement for sustainable aviation. By pooling financial resources and expertise, SAF projects can be effectively transferred from the development phase to the industrial scaling phase.[155]

6.3.2 Scalability

SAF has great potential to shape the future of aviation, provided that large-scale and cost-effective application can be guaranteed.[169] The greatest challenge exploiting this potential lies in scalability.[169] This is considered a critical success factor for the decarbonization of the aviation sector and is essential to close the predicted supply gaps (see chapter 4.3). In order to meet the demand for SAF, production capacities must be expanded significantly more than planned according to previous project announcements.[56]

Successful scaling of SAF production and use depends on various factors. Five areas can be defined that have a significant influence on scalability:

- **Technology:** SAF production technologies are still in development, with PtL in particular requiring further advancement to enable industrial-scale e-SAF production. This progress is essential not only for scaling up output but also for improving economic viability through cost reductions.[56]

  Here, quick progress is crucial. Immediate action is essential due to the long planning and development times of SAF projects.[97]

- **Infrastructure:** For an efficient ramp-up, it is necessary to establish specialized infrastructure for the trade and transport of SAF between the main producers and the customers. These so-called net-zero corridors should connect areas that offer a high availability of raw materials with those that are particularly suitable for production and with the customers.[97]

- **Economic efficiency:** This applies to both the production and the use of SAF. Both must be economical to be viable in the long term. On the demand side, the cost gap between SAF and conventional kerosene must be closed – eliminating the so-called "green premium". On the production side, profitability must be ensured. This means not only avoiding losses in SAF production, but also achieving returns that are at least comparable to those of other renewable fuels that can be produced using the same facilities. Only then can full utilization of available production capacity be realized.[56]

- **Regulation:** The favorable prices for fossil fuels make it unlikely that market dynamics alone will make SAF production sufficiently attractive. For this reason, regulatory incentives are needed that either make fossil fuels less attractive (e.g., taxes or penalties) or make SAF more attractive or even require the use of SAF (e.g., SAF quotas in the EU). In addition, the creation of new state financing options can boost SAF production by ensuring economic competitiveness.[97]

> A regulatory framework is essential for investment security. Policymakers must create additional financing instruments to close the financing gap caused by technical, regulatory and market risks. So far, the investor cannot bear these costs alone.
>
> **Dr. Mark Misselhorn,** Chief Executive Officer, Caphenia GmbH

Both national and cross-border regulations are needed to address the international nature of aviation. International coordination is necessary to prevent a shift in airline business activities to countries with less stringent requirements (the so-called carbon leakage).[56]

One particularly important regulatory aspect is the standardization of book-and-claim systems. It is necessary to ensure the reliable and unambiguous accounting of CO_2 savings through SAF use. This applies in particular to the supply contracts described in section 3.3, in which, in the absence of suitable infrastructure, one party purchases SAF and accounts for its CO_2 savings, while another party physically uses the fuel.[97]

Regulations also play an important role in creating the other prerequisites for scaling up SAF and promoting its increased use.[56] One example of this is the requirements and mandates in the ReFuelEU regulation, which prescribe the use of a certain proportion of SAF on flights. On the other hand, there are already political means of incentivizing the production of SAF. These include, for example, tax breaks introduced in the USA under the Sustainable Skies Act, which increase the profitability of SAF production. Steady, forward-looking and predictable political support enables long-term planning security for producers and customers, for example by ensuring high demand in the long term.[97]

- **Sustainability:** Even if its use always contributes to decarbonization, SAF is not automatically sustainable in every respect. This is because there are other important aspects to consider in addition to climate change (see chapter 7). In the case of SAF, these include biodiversity and land use, as well as the social impact of production. In particular, it is important that sufficient sustainable raw materials such as waste mass are available and used for bio-based SAF instead of food-grade plants. In the case of E-SAF, the origin of the CO_2 required is just as important as the use of exclusively renewable energy and green H_2. Certificates play an important role in creating credibility and transparency here.[56]

Sustain
ability

As the regulatory aspect has already shown, these five areas overlap and are in part strongly interdependent. For this reason, a holistic approach is necessary in order to successfully scale SAF.[169,56] Such an approach can be supported, among other things, by collaboration between various parties involved (airports, airlines, producers, etc.), and can be seen, for example, in the form of the supply contracts discussed above or the alliances already established.[56, 169] Going forward, greater focus will be needed to align stakeholder interests and ensure long-term planning certainty. In addition, significant investments are necessary to fulfill the above-mentioned requirements for scaling.[97] In particular, research and the further development of production technologies should be focused on.[170]

Taking all these preconditions into account, experts believe that sufficient scaling is possible to achieve the decarbonization targets, provided that all possible measures are taken. Regulatory support in particular will determine success or failure.[169] When assessing the scaling potential, however, a distinction must be made between E-SAF and Bio-SAF. Bio-based SAF has the greater potential for scaling in the short and medium term. This is due to the more advanced technological maturity and the currently good availability of biomass as a raw material. In addition, this is one of the reasons why bio-based SAF has a lower price than E-SAF.

In the long term, however – assuming the challenges regarding the necessary technological progress are overcome – E-SAF has the greater potential for scaling up to the quantities required for aviation, while maximizing the potential for decarbonization. These challenges include the availability of sufficient green H_2 at prices that enable economic production and sufficient storage options for renewable energy. In addition, the development of DAC technology and other sustainable sources of CO_2 are necessary to enable CO_2 production on an industrial scale. If all these aspects are in place, E-SAF has immense scaling potential due to the almost unlimited availability of the materials required for production.[171]

E-SAF also requires significantly less land use in its production, which is, apart from the climate effect, generally more sustainable than Bio-SAF.[172] Logically, this only applies if renewable energies and green H_2 are used. The German company atmosfair, which produces E-SAF in a PtL plant in Emsland, even goes so far as to say that E-SAF is the only long-term sustainable fuel option for air travel. The company justifies this with the inevitably very large biomass requirement when scaling up Bio-SAF, which requires substantial agricultural acreage. A conflict of interest with the food supply would be unavoidable here in the long term if sufficient production were to cover the total global demand.[171]

> “Although biomass is available today, its availability will be limited in the future. It is unlikely that the supply will be sufficient to meet the growing demand. In addition, biomass-based SAF may not be completely CO_2-neutral in the future either.

Bernhard Dietrich, Head of CENA Hessen| Hessen Trade & Invest GmbH

ESG impact on global SAF projects

7

Introduction and summary of the chapter

A significant driver for the use of SAF is the reduction of greenhouse gas emissions. However, it is essential that both the production and use of sustainable fuels follow a holistic approach — one that balances economic viability with environmental and social sustainability. In addition to far-reaching opportunities and potential for society, the environment and regulation, the use of SAF also carriers risks that need to be managed. The management of environmental, social, economic and regulatory impacts is of great importance for successful and sustainable SAF development and production.[173] The need for effective management is reinforced by the problem of trade-offs between different ESG aspects.[174]

This requires the development of innovative and well-founded framework conditions that enable sustainable project development and promote the exploitation of potentials and opportunities in SAF projects.

In the area of the environment, measures to minimize energy consumption, water use and land requirements should generally be considered. Sustainable cultivation methods, the selection of suitable cultivation areas, the optimization of waste management and the diversification of raw materials are important topics specifically for bio-based SAF. E-SAF requires the creation of framework conditions for the circular use of materials, the construction of seawater desalination plants and the use of sustainable sources of CO_2.

From a social perspective, the creation of jobs and the integration of the local population into decision-making processes are relevant. Bio-based SAF also requires measures to safeguard health, guarantee food supplies and ensure occupational health and safety. E-SAF can contribute to an improved power supply for the local population through suitable framework conditions.

Regulation and governance encompass the creation of financial support opportunities, a unified regulatory framework, and the consideration of consistency as well as flexibility. The bio-based SAF industry requires specific guidelines for the use of biomass and to avoid competition with the food industry. The E-SAF sector requires regulatory support for the production and development of PtL technology, regulation of carbon sources and large-scale infrastructure measures. Standardized CO_2 accounting is also of great importance.

This chapter first addresses the challenges and risks associated with the production, use and scaling of SAF and then focuses on the potential benefits for sustainability in the areas of environment, society and regulation. It then discusses some exemplary framework conditions that are crucial for the successful implementation of sustainable SAF projects. This is followed by a differentiated consideration of organic and e-SAF, whereby some aspects apply to both types and are therefore analyzed together.

7.1 Overview of challenges, risks and opportunities with a focus on ESG

When analyzing the impact of SAF on the ESG criteria, the specific influences on the environment, social aspects and governance are examined.

In the **environmental area,** the focus is particularly on the impact of SAF on the climate, biodiversity and ecosystems. This results in opportunities to reduce greenhouse gas emissions and optimize waste management. One of the potential risks associated with scaling SAF production is land-use change, which can often result in negative environmental impacts. Furthermore, specific production processes and conditions such as the operation of seawater desalination plants (E-SAF), the demand for rare metals (E-SAF) or energy intensity (Bio-SAF) can represent additional environmental burdens.

In the **social area,** the influence of SAF on the local society at the production site is examined. There may be opportunities such as the creation of new jobs, the promotion of economic development and improvements in the local food supply (Bio-SAF), for example, by generating plant-based proteins as a valuable by-product. Challenges include the appropriate integration of affected stakeholders, the loss of jobs and the emergence of land use conflicts.

In the area of **governance,** the development of regulations for land management (Bio-SAF), waste management (Bio-SAF) and renewable energies (E-SAF) is important. It should be noted that waste and residual materials are often subject to different regulations, which can pose a challenge. The establishment of long-term, internationally valid and standardized certification measures and sustainability criteria presents a major challenge. However, regulatory instruments offer the opportunity to effectively control SAF production and use and minimize risks and hazards.

ESG

Table 12

Overview of challenges and potential for organic and E-SAF according to ESG criteria

(Source: EY)

Effects ESG	SAF type	Challenges and risks	Potentials
Environment (E)	Bio-based SAF	■ The production of bio-based SAF is an **energy-intensive process**. A lot of energy is consumed during the biomass harvest that can affect the carbon footprint of the fuels. The conversion of biomass into Bio-SAF, by fermentation and distillation, also requires a high energy input. In addition, the transportation of the biomass requires energy, with the energy consumption varying based on the distance between the processing plant and the cultivation area.[175] ■ Bio-based SAF generally has a positive climate impact due to CO_2 sequestration during during biomass growth. However, the net effect of carbon sequestration depends on sustainable cultivation practices. **Land use changes** can increase **greenhouse gas emissions** from soil and vegetation, which can offset the positive CO_2 sequestration. Biomass cultivation for bio-based SAF can cause environmental impacts such as soil degradation, deforestation and loss of biodiversity habitats.[175] ■ The cultivation of biomass crops is characterized by **water intensity** and can lead to water stress and deterioration of water quality in vulnerable regions due to runoff of fertilizers and pesticides. Effective water management is required to minimize the impact on water sources and aquatic biodiversity. This includes efficient water use, the use of water-saving irrigation systems and the cultivation of plants with low water requirements.[175] ■ The use of fertilizers and pesticides in organic farming leads to nutrient pollution and impairs **biodiversity and soil health**. Monocultures cause soil depletion and an increased dependence on agricultural chemicals. These effects can be reduced through sustainable cultivation methods such as the use of catch crops, crop rotation and the cultivation of less demanding plant species that maintain the balance. ■ Another risk of biomass cultivation is the **spread of invasive, non-native species**. Plants that are suitable for biomass production are often characterized by high productivity, low input and broad environmental tolerance. They can spread in the natural ecosystem, impair ecosystem services and displace native species, which has consequences for the ecological balance and biodiversity. The control of invasive species requires considerable financial resources.[174]	■ Bio-based SAF has a **positive impact on the carbon footprint** due to its potential to reduce aviation fuel emissions. In 2017, NASA investigated the impact of a 50% mix of Bio-based SAF on emissions and the formation contrails. Contrails can develop into cirrus clouds and negatively affect natural weather processes. It is assumed that contrails have had an even greater impact on the atmosphere than CO_2 emissions since the beginning of aviation. The analysis showed a reduction in particulate emissions of 50%–70%.[176] For a MJ of bio-based SAF based on camelina oil (HEFA) produces 44 g–47 g CO_2 equivalent (compared with 78.3 g/CO_2 per MJ of conventional kerosene.[177] ■ Scaling up bio-based SAF has the potential to reduce the environmental impact of **waste recycling**. Waste is usually disposed of in landfills, which contributes to environmental degradation, so converting parts of the waste to bio-based SAF is of interest.[178] In addition, the use of waste and residues from biomass offers the advantage that less land needed for landfills or biomass cultivation areas. Bio-based SAF production thus leads to environmentally **friendly waste management and the circular economy**.[179] The degradation of plastic takes many hundreds of years, and disposal methods such as incineration or landfill pollute the environment. Thermal processes could be used to convert plastics into hydrocarbons and use them for fuel production. However, this process requires increasing development and research as well as government support.[180]
	E-SAF	■ Given that electricity from existing grids is often based on a high proportion of fossil fuels, it is unsuitable for E-SAF production in many places. It is, therefore, essential to develop renewable energies for E-SAF production.[75] The challenge of its availability arises from the increasing **demand for renewable energies** in many sectors. The WEF warns that H_2 production and electricity generation from renewables are not secure due to phenomena such as reduced wind speeds worldwide, water scarcity in many regions and the threat to hydropower from droughts.[181] The risk of unavailability of green energy could lead to a reliance on traditional fossil energy sources.	■ Like Bio-SAFs, E-SAFs contribute to the **reduction of greenhouse gas emissions**. The use of E-SAF makes it possible to the enormous potential of renewable electricity by using sources such as the sun and wind. In combination with a sustainable source of CO_2 such as DAC, this technology offers a sustainable solution for aviation.[182] E-fuels generally have a very low impact on the climate, even if they are not completely climate-neutral due to the unavoidable residual emissions from the construction of wind power and photovoltaic plants, for example, but also from transportation and distribution.[75] The total emissions for production per MJ of fuel at 5–10 g CO_2 eq.[182] Classic kerosene has emissions of 78.3 g/CO_2 eq. per MJ.[177]

Effects ESG	SAF type	Challenges and risks	Potentials
Environment (E)	E-SAF	The expansion of E-SAF can have a **"lock-in effect"** that prevents the environmental potential of SAF from being fully exploited. The use of industrial CO_2 can inhibit further development of technologies (such as DAC) and the decarbonization of sectors. In addition, the use of E-SAF can reduce the pressure to further develop innovative solutions for the development of flight concepts that do not use carbon-based aircraft fuels.[182] Electrodes made of **metals such as platinum or iridium** are required for the electrolysis process. These materials are rare and there are only a few mining sites. The recycling of these metals has also only been carried out to a limited extent to date. Promoting the circular use of raw materials and advancing research aimed at reducing their consumption are essential steps to minimize environmental impact. To produce one liter of E-SAF (0.0008 tonnes), 3.6 liters of drinking water quality are required. In regions with high solar energy potential – ideal for renewable energy production – water availability is often limited. This means that seawater desalination plants have to be used, which, in turn, should be be powered by renewable energy.[75] The energy consumption of **seawater desalination plants** is very high. Moreover, the by-product of desalination – salt sludge – requires careful disposal due to its considerable environmental impact. The return of the salt sludge to the oceans leads to the creation of toxic zones with extremely high salt content and high quantities of harmful elements. Inadequate dilution of waste can lead to dead zones due to oxygen deficiency and contamination.[183]	
Social (S)	Bio-based SAF	The risk of insufficient **involvement of the local population** and **public acceptance** is relevant, as with many large-scale infrastructure projects. Both bio-based SAF and E-SAF projects require significant land use. Bio-based SAF requires large areas for the cultivation of energy crops. Inadequate consideration of local communities can lead to conflicts over land use rights.[75] Therefore, it is important to grant civil society a comprehensive say in the matter. The **"Food vs. Fuel" dilemma** must be considered for bio-based SAF production, which describes the competition for land between agriculture and the biofuel industry. This raises concerns in politics and academia due to global population growth and increasing demand for food. Solutions include the efficient use of marginal land and the concept of multiple land use. The use of sustainable bio-based raw materials, such as lignocellulosic biomass and algae, should be promoted, although the commercial distribution of algae-based fuels is not yet widespread due to high technology costs and cultivation limitations. Another issue that could arise from bio-based SAF production is an increasing **health risk** for the local population at the production site.[184] Under various tests approaches the health impacts in biofuel production regions were worse than those associated with the production of fossil aviation fuels. This causes are linked to the cultivation of biomass, H_2 production and the processing of biomass, none of which is required for conventional aviation fuel.	The implementation of bio-based SAF can, in the long term, also promote the **health of the population** through emission reductions, improved waste management, and access to transportation systems.[178] IRENA highlights that more and more cities are facing an increase in waste due to the expansion of landfills. This problem can be countered by using waste as a raw material for SAF.[179] There is a study[174] predicts that by 2050, up to 40 million **new jobs** could be created in the bioenergy sector. These jobs will be distributed along the entire value chain, with a particular increase expected in the agricultural sector. This leads to higher incomes for farmers and promotes local economic development. Despite ongoing debates around the "Food vs. Fuel" dilemma, **positive synergies can arise between food supply and biofuel production** if managed appropriately. These include creating income sources for farmers, improving crop cultivation for food, expanding agricultural infrastructure, and procuring agricultural inputs that enhance its potential.[174] Efficient food system management – especially through fair distribution and reduced food waste – can help free up resources for bioenergy production.[179]

<table>
<tr><th>Effects ESG</th><th>SAF type</th><th>Challenges and risks</th><th>Potentials</th></tr>
<tr><td rowspan="2">Social (S)</td><td>Bio-based SAF</td><td>

The cultivation of biomass requires considerable amounts of water for irrigation. According to calculations by the Potsdam Institute for Climate Impact Research, without sustainable water management and in light of ongoing population growth, the number of people living in regions affected by severe water stress is expected to rise significantly by the end of the century. Regions that are already suffering from water stress today would be the most affected, for example, the Mediterranean region, the Middle East, north-eastern China, south-eastern and southern West Africa.[185] However, by-products of agricultural cultivation, such as oil from soybean cultivation, are often used as biomass, meaning that the water demand here is a consequence of food cultivation. One potential solution to water scarcity is the cultivation of halophytes as biomass crops, as they can thrive in saline conditions and be irrigated with saltwater.[186]
In the production of bio-based SAF, a lack of engagement in occupational health and safety can pose a risk to workers. It is important to recognize the hazards associated with SAF production and take appropriate measures for the health of the workforce. While SAF plants have fewer occupational health issues than the fossil oil and mining industries, worker fatalities, injuries and illnesses are a serious concern. The hazards associated with bio-based SAF production are biological, chemical and physical in nature.

Biological hazards: These include the spread of respiratory and infectious diseases due to exposure to organic materials from bio-based SAF production.
Chemical hazards: The release of hazardous contaminants and chemicals from municipal waste poses a challenge.
Physical hazards: Handling of machinery in bio-based SAF plants can lead to injuries.[178]

</td><td>

The development of bio-based SAF production is expected to have a positive impact on the economic development of the producing regions. This includes the creation of new jobs, an increase in GDP, as well as promotion of trades in regions where the cultivation of raw materials is possible.[184]
The use of biogenic residues can help to reduce competition between food production and fuel production and improve other value chains.
</td></tr>
<tr><td>E-SAF</td><td>

The risk of a lack of involvement of the local population and public acceptance should also be taken into account for E-SAF initiatives. In particular, E-SAF projects require land for production facilities and the generation of renewable energy. Conflicts of interest with the local population should be avoided here.
The production of E-SAF harbors the risk of conflicts with the local power supply and the energy transition. Countries with good production conditions for E-SAF often have an inadequate or fossil fuel-based electricity supply.[75] This means that renewable energy capacities are needed to supply the local population and local industry and compete with energy consumption by E-SAF and its export.
Another risk is the loss of jobs due to the migration of parts of the economy to regions that are advantageous for renewable energies or due to the reduction of jobs in the fossil energy sector. It is necessary to support social change and the transition of workers into new fields of work, for example by offering retraining and training.[75]
</td><td>

In the long term, the implementation of E-SAF, similar to Bio-SAF, can contribute to the promotion of economic development and local value creation. To achieve this objective, actors along the entire value chain, both upstream and downstream, must be integrated into the value chain. In the long term, this can lead to sustainable economic development, for example through creation of new companies, knowledge growth and innovation. Job creation is another positive development that, according to Agora, goes hand in hand with e-fuel production.[75]
</td></tr>
</table>

Effects ESG	SAF type	Challenges and risks	Potentials
Social (S)	E-SAF	■ E-SAF expansion can have a negative impact on the local population due to the high demand for water, especially in water-scarce regions. In addition to the electrolysis process, cooling and cleaning processes additionally consume water, although the latter can be covered by recycling water from the electrolysis process. In general, the water consumption of E-SAF is considerably lower than that of Bio-SAF, with the water footprint of one liter of bio-based SAF (0.0008 tonnes) being increased by a factor of over 5,000 compared with one liter of E-SAF (0.0008 tonnes).[182] ■ The **land required** to produce E-SAF can compete with food production, mainly due to the production of renewable energy. In comparison, the areas required for the provision of CO_2 (for example through DAC), for water electrolysis and for fuel storage are significantly smaller. The amount of land required for photovoltaic systems is significantly greater than for onshore wind systems. The best land areas for solar energy production are desert-like regions with high levels of solar radiation, which are not suitable for agricultural use.[182] The use of agrivoltaics could be a strategy for using land for both photovoltaic systems and agriculture.[187]	■ In addition, E-SAF offers opportunities to support financially weak countries in **financing the implementation of renewable electricity supply**. This is often associated with high costs, so that investments in power generation plants in the context of E-SAF projects offer the opportunity to expand the local infrastructure. In this context, it would be necessary to build additional power generation plants and thus increase capacity. In addition, the electricity grid should be expanded as part of E-SAF projects.[75] The high demand for green H_2 can create momentum for the establishment of H_2 value chains and improve access to transportation.[182]
Governance (G)	General	■ Technological and transformative changes are increasing pressure on governments to create a **common regulatory framework**. This is challenging as traditional regulations are often focused on specific topics and sectors and do not always harmonize with new developments.[188] The introduction of SAF requires greater integration of different sectors (e.g., agriculture, transportation and aviation) and thus cooperation between traditionally separate industries.[189] ■ Governance challenges can also arise from requirements, which can lead to **market entry barriers** for new competitors and consequently hinder innovation.[188] ■ The OECD points out that **traditional regulations** are not always transferable to new situations, products and technologies, which also applies to SAF.[188] Regulatory authorities must therefore constantly adapt their approaches and make them flexible. ■ Traditional **liability concepts** do not always apply to new developments.[188] Many players are involved in SAF production, which makes it difficult to clarify liability for risks and damage. Regulations must assign clear responsibilities here. ■ The **international coordination** of regulations and governance also poses a difficulty, as the production and use of SAF takes place across borders and therefore requires coordinated international regulation. There is a risk that companies will use the "forum shipping" technique to choose jurisdictions that offer them the most favorable conditions, allowing them to circumvent regulatory requirements.[188] Effective SAF regulations must take into account the geographical, economic, social and political differences between nations. Different supply and demand structures and policy instruments must be adapted to the specific conditions of countries, such as availability of raw materials, maturity of value chains, energy dependency and climate targets.	■ Regulations must be created towards short, medium and long-term effectiveness to **guarantee security for investors and producers,** drive infrastructure expansion and expand SAF capacities.[189] ■ SAF policy and cooperation with SAF supply chains can promote **research and development of new production routes**.[189] ■ Regulatory measures must be taken **to facilitate market entry for new competitors,** for example through transparent regulatory policies, simplified approval procedures and financial incentives, to remove barriers to market entry for SAF producers and consumers. ■ **Flexibility** to ensure adaptation to different situations and priorities is very important. This enables guidelines to be rapidly adjusted in response to technological advancements. ■ A regulatory policy that is characterized by long-term security can create **investment incentives** and thus drive the production and use of SAF. ■ Subsidies, tax breaks and other financial incentives are designed **to offset the higher costs** of SAF compared with conventional kerosene.[191]

Effects ESG	SAF type	Challenges and risks	Potentials
Governance (G)	General	■ **Facilitating the certification** and quality of SAF supply chains are subject to sustainability standards.[189] Clear certifications promote trust, better market access and can provide investment security. ■ In general, **limited public awareness** of SAF and underdeveloped social research hinder the design of effective SAF policy and regulation.[188] The aviation industry's lack of support for policies aimed at increasing the cost of air transportation, subsidies, or limiting the growth in air traffic volume is further challenging.[190] ■ Projects in the energy sector, which are often associated with **large land claims,** can lead to a disregard for land use rights, particularly in unstable countries. To prevent this, effective governance structures are needed that actively involve local stakeholders. Measures such as transparent complaints mechanisms and the creation of dialog formats with civil society can contribute to this.[75]	■ When developing guidelines, price sensitivity to external effects such as environmental damage must be taken into account. An appropriate assessment of these costs can contribute to **improving the market conditions for SAF**. ■ Easy-to-implement regulations promote the **acceptance and implementation** of SAF projects by the stakeholders involved and facilitate effective cooperation between regional and national authorities. ■ It is important to predict the **unintended consequences** of implementing regulation and to counteract social, economic or ecological risks through forward-looking political measures. ■ A robust SAF policy is characterized by resilience and the ability to **achieve defined objectives**.[191]
	Bio-SAF	■ In the area of **land management** for Bio-SAF, regulations should aim to prevent negative impacts on food security from the cultivation of energy crops. The amount of bio-commodities grown affects land use and food prices, which underlines the need for regulation.[192] It is challenging to define policies that prioritize both food security and feedstock production for bio-energy production. Second-generation residual biomass competes less with food security and at the same time can improve energy efficiency and security. Therefore, policies should be developed that promote the use of residual biomass and agricultural waste instead of first-generation feedstocks.[178] ■ In the area of **waste management,** regulations are also crucial to the promotion of SAF. These concern the handling of production by-products and waste that can be used for the production of advanced Bio-SAF. In the future, governments should encourage farm owners to convert waste and residues into useful products. They should offer incentives as well as tax breaks.[193] The current regulations on the definition of waste, by-products and co-products should be taken into account. In some cases, these products are subject to different regulations at the same time, which means that their implementation for biofuel production can be complex. In the EU, details are explained and defined in RED II, in particular. For example, products and by-products must not be deliberately and demonstrably "converted" into waste and residues, e.g., through incorrect storage or incorrect declaration when imported from abroad to the EU.	■ See Governance in general.

Effects ESG	SAF type	Challenges and risks	Potentials
Governance (G)	Bio-SAF	■ **International and effective certification systems** must be developed to determine which biomass sources are classified as sustainable. The EU's RED II, for example, restricts the use of biofuels with a high risk of land use in areas with high carbon stocks, such as those based on palm oil, in order to avoid conflicting objectives and limits the proportion of biofuels based on food raw materials.[194] The EU already has an ISCC (International Sustainability & Carbon Certification) certification scheme to certify compliance with the criteria of RED II. It even goes beyond the legal requirements of RED II, as it also covers environmental and social requirements.[195] ■ **Incentive policies** are crucial for the promotion of biofuels. In the U.S., Brazil and the EU, subsidies, blending targets and tax exemptions have already significantly increased the consumption of biofuels. Direct subsidy measures for farmers and companies growing biofuel feedstocks reduce production costs and increase the supply of Bio-SAF. Tax benefits for biofuel producers and consumers are necessary to ensure competitiveness with fossil fuels. The promotion of research and development accelerates innovation and technology development. To enable the use of biofuels on a large scale, investment is needed in the infrastructure of production and distribution facilities, particularly to promote the production of second and third-generation biofuels.[175] ■ In the short term, regulatory systems must balance **raw material availability and sustainability** and integrate flexibility, especially during industrial scaling. ■ The regulatory promotion of **education, training and certification of personnel** is an essential aspect for the production and further development of bio-based SAF. Knowledge in areas such as biotechnology, environmental management and agriculture is important.	
	E-SAF	■ **Certification measures** to ensure that E-SAF has been produced sustainably must be developed. This includes, in particular, ensuring that CO_2 and electricity comply with sustainability standards. One example of a global certification system is the ISCC (International Sustainability & Carbon Certification), which supports E-SAF and the certification of raw materials. It is compliant with the sustainability requirements of the EU, Japan, Australia and CORSIA.[196] ■ In addition, **carbon sources and infrastructure must be regulated** to ensure the safe and sustainable use of CO_2 from the atmosphere or industrial facilities. It must also be determined how CO_2 emissions are included in the overall balance of the fuel. In February 2024, the EU Commission presented the "Industrial Carbon Management" strategy, a regulatory framework that describes the future need for sustainable CO_2 for the transport and mobility sector, including E-SAF. Despite the further development of carbon management in recent years, the framework lacks regulatory certainty and political coherence incentives for investments in CCU (carbon capture and utilization) systems. For example, only CO_2 pipelines that transport CO_2 for permanent storage are covered by the EU taxonomy. Those for CCU or e-fuel production are not EU taxonomy-compliant. This leads to a lack of private investment.[197] ■ According to Agora, the policy focuses on promoting research and development to optimize production processes for e-fuels and to sustainable sources of CO_2, which indicates that regulatory systems are also indispensable in this area.[75] ■ In general, supportive **financial measures** must be taken, such as tax breaks, subsidies and grants,[198] as both producers and consumers face high price barriers to the production and purchase of E-SAF.[199] This support can be provided not only through direct measures for E-SAF but also through indirect support for renewable energy sources.[198] IATA emphasizes that governments must ensure that support for renewable fuels and renewable energy is expanded. By 2023, most countries worldwide were subsidizing fossil fuel production.[189] ■ The **education, training and certification of personnel** should also be promoted through specific regulations.	■ See Governance in general.

7.2 Framework conditions and measures to minimize ESG risks

To adequately manage and effectively reduce the challenges and risks associated with the scaling of SAF described in chapter 7.1, it is necessary to consider the ESG framework conditions and take appropriate measures. The following section presents some approaches that enable the sustainable production and use of organic and e-SAF.

> The use of renewable energy sources is always limited and associated with competition regardless of which renewable sources are used. One advantage of biomethane, as used by Caphenia, is its significantly lower energy consumption. In the long term, biomethane will certainly also be fed into the electricity grid as soon as the corresponding infrastructure is developed.
>
> **Dr. Mark Misselhorn,** Chief Executive Officer, Caphenia GmbH

7.2.1. Environmental area (E) for SAF projects

1 | Bio-based SAF – Production and energy consumption

As the production of **bio-based SAF** is energy-intensive, **measures to minimize energy consumption** are essential. This can be achieved by using efficient harvesting techniques, optimizing logistics and increasing process efficiency.[175] For example, the optimization of sustainable logistics and transport across the entire supply chain requires the efficient design of all transport processes. Factors such as the average transport distance, the biomass density and quantity, the carrying capacity and the speed of the transport vehicle must be taken into account.[200] The new generation of SAF production, such as the use of algae or bacteria, can be interesting for optimized energy consumption. For example, cyanobacteria can produce hydrocarbons such as alkenes from sunlight and atmospheric CO_2.[175] Through genetic manipulation, certain enzymes in cyanobacteria are inhibited to maximize hydrocarbon production. This enables the natural production of alkenes, which are then further processed by hydrotreatment, like the HEFA process. The use of genetically modified cyanobacteria is a promising approach to avoid excessive land use, interference with natural ecosystems, the spread of invasive plant species and the release of greenhouse gases. However, this approach requires further intensive research and development.

To minimize the risk of invasive species and environmental harm from pesticide and fertilizer use in agriculture, sustainable cultivation practices can be implemented. These include the use of catch crops, cover crops, crop rotation, and resilient plant species that require minimal chemical inputs and water.[175] Cover crops are cultivated between the main growing seasons to produce fodder and green manure.[201] The catch crops are, therefore, not primarily intended for sale. For example, the plant species Brassica carinata (B. carinata) can be planted as an intercrop to be used later as a raw material for bio-based SAF production. The British oil company BP has already started to use oil from B. carinata on a small scale for biofuel production. BP refineries in Germany successfully demonstrated in 2023 that B. carinata oil can be processed together with crude oil in existing plants.[202] Cover crops are sown above another crop (undersown) so that a vegetation cover is still present after the cover crop is harvested, making the soil less susceptible to compaction and making it more stable in wet seasons. In addition, the cover crop can also be used as livestock feed.[203] Crop rotation also offers numerous benefits, including improving soil fertility and reducing the need for chemical fertilizers through the alternation of cultivated plants and the associated varying nutrient consumption.

In addition, crop rotation helps diversify income sources for farmers who want to engage in renewable energy.[204] Chevron Corporation is working with Bunge and Corteva to utilize WOSR as part of a crop rotation for biofuel production. This crop offers similar benefits to conventional inter-crops, including improved soil health, reduced water and nutrient runoff, and carbon storage in the soil.[205]

The careful **selection of areas** for biomass cultivation is crucial to protect the environment and biodiversity. Preference should be given to land that has already been degraded in order to minimize the negative impact on untouched ecosystems. It is also important to select sites whose conversion to agricultural land does not lead to the release of stored carbon stocks, as would be the case if forests and savannahs were cleared.[175] The United Nations Framework Convention on Climate Change (UNFCCC) establishes in the CDP Executive Board Report that sustainable biomass should be cultivated on areas such as forest, arable, and pasture land while maintaining the respective land types or practicing sustainable management to preserve the level of carbon storage in these areas.[206]

Efficient water management is important to **minimize water consumption** when growing biomass. This includes the cultivation of plants that require less water. It is also advisable to choose cultivation areas that have naturally sufficient water supplies. Multifunctional plantations offer another effective approach. Certain forms of vegetation, such as forests and shrubs, can serve as natural filters for treating nutrient-rich water, for example, for wastewater from households, agricultural runoff or leachate from landfills. Ground cover plants control water erosion, reduce direct surface runoff, filter sediments and reduce the risk of landslides.[207] The use of innovative and efficient irrigation techniques is also an important aspect. Drip irrigation systems enable an objective water supply and ensure that the water penetrates deep into the root layer, significantly increasing water use efficiency.[208]

Ultimately, using halophytes as biomass, such as the genera Salicornia or Suaeda, proves to be an innovative approach to address the increasing scarcity of irrigated land and the rise in soil salinization. Halophytes can grow in very high salt concentrations, allowing them to be irrigated with seawater. Both the oil from the seeds and the lignocellulose biomass can be used for biofuel production. In addition, the cultivation of halophytes is associated with reduced energy costs.[186]

The optimization of waste management through the expansion of bio-based SAF is only possible through an increasing focus on second, third and potentially fourth-generation fuels. Although these generations of SAF are still in their infancy and are not available in large quantities, they mark an important step towards more sustainable SAF production.[209]

An outstanding example of efficient waste management is the city of Oslo. Between 2016 and 2019, 16 to 19 kilotonnes of household food waste (around 50% of total household waste) was collected there. In total, Oslo delivers 30 kilotonnes of food waste and wet organic waste to the biogas plant in Romerike, taking into account additional industrial and commercial waste.[210] In the future, this model could also be adapted to biogas production to produce bio-SAF.

Bio- and E-SAF

2 | E-SAF — Production and energy consumption

The efficient production of E-SAF makes the most sense in places with a high potential for renewable energy, such as Australia, South Africa, the Gulf States and Chile. This helps to overcome the problem of limited availability of renewable energy in some regions.

The generation of renewable energy near production sites is another strategy. This not only reduces the energy demand for transportation but also minimizes emissions. Shorter transport distances also mean lower energy losses, thereby increasing overall efficiency. In general, the expansion of renewable energy is essential to advance the scaling of E-SAF. The share of renewable energy in the power grid should be consistently increased.[211]

To save CO_2 and transportation costs, the book-and-claim system (see Chapter 5.1) allows for the use of SAF near the production site. This system avoids long transport distances and additional greenhouse gas emissions.[212]

Promoting a **circular use of materials and raw materials** and developing **alternative materials** for electrolysis systems help reduce dependence on critical raw materials such as platinum and iridium in electrodes. Iridium, a rare metal, is increasingly being replaced by more robust materials. The companies Sibanye-Stillwater and Heraeus have developed ruthenium-based catalysts for PEM electrolysis that offer great potential, as ruthenium has 50 times the mass activity and higher catalytic activity than iridium. Ruthenium can also catalyze the O_2 evolution reaction, an important step in electrolysis. However, as it is not as stable as iridium, a combination of both metals was used for this development.[213]

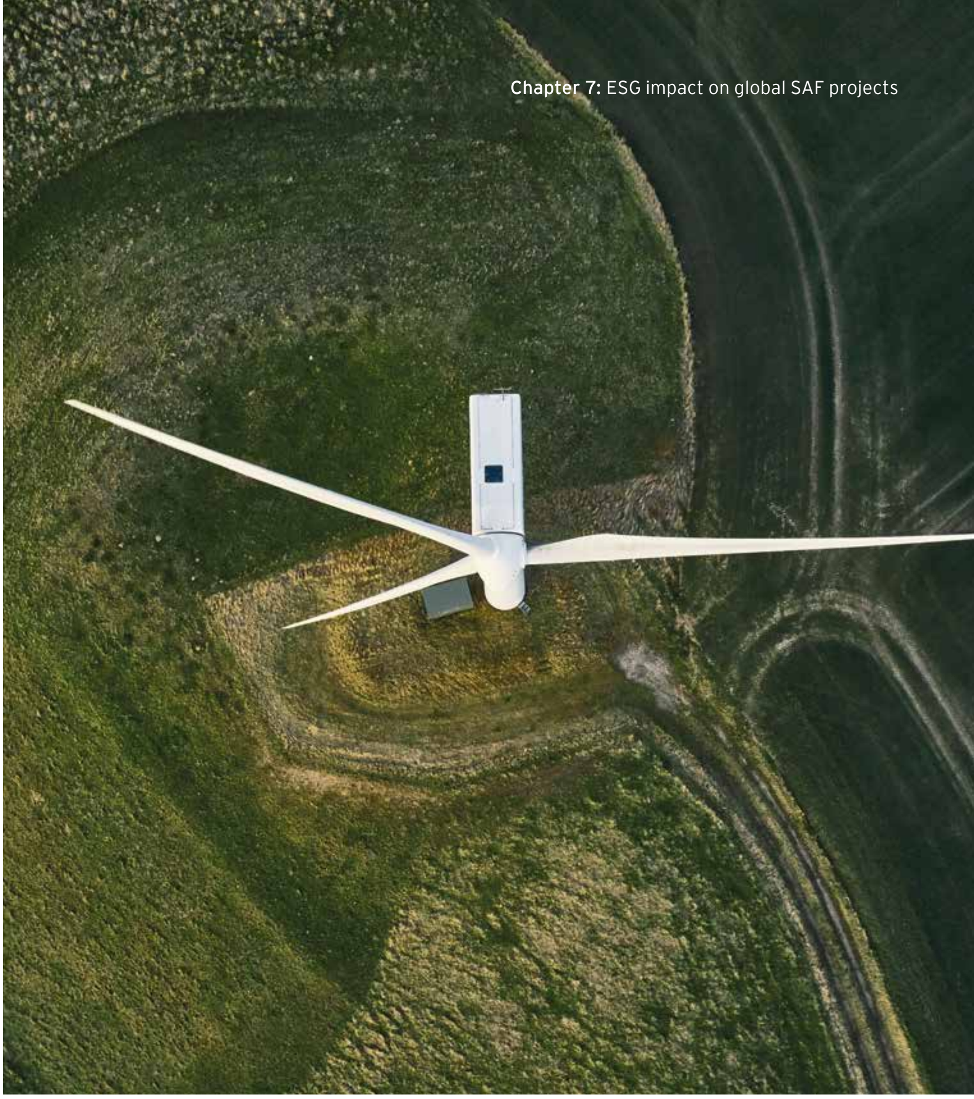
Recycling materials from electrolysis fuel cells at the end of their service life supports the circular use of raw materials. Bosch is working on technologies to recover and recycle platinum from fuel cells. According to the company information, recycling can lead to a reduction of up to 95% in CO_2 emissions caused by the degradation of platinum. This process is also economically advantageous. As platinum is needed in many industrial sectors, such as medicine and the automotive sector, the sustainable use of this raw material is essential in the future.[214]

The construction of **sustainable seawater desalination plants** is an effective strategy to counteract the high water demand for E-SAF production. The Global Clean Water Desalination Alliance set a global goal in 2015 to achieve a Clean Energy Target of 70% to 100% for all newly built desalination plants by 2036–40, thereby expanding operations based on sustainable energy sources.[215] Electrolysis systems require high-purity water, which is obtained by removing dissolved salts and minerals from seawater. This water treatment, which is usually carried out using multi-stage flash evaporation technology, has a high energy requirement. Research is already being carried out into electrolysis processes that use seawater directly, on the assumption that this will reduce energy consumption.[75] However, the WEF found that this approach only generates marginal energy savings. Instead, the organization recommends reducing the plant's energy efficiency and costs to enable sustainable E-SAF production.[216]

An additional measure to increase efficiency and reduce water consumption in the production process is the implementation of **efficient water utilization technologies** in H_2 electrolysis. For example, dry cooling processes can be used. It is also important to recycle excess water from electrolysis and make it usable for other purposes.[217]

Plugpower, a US company specializing in the production of H_2 and fuel cells, is planning to build an H_2 plant in California (Mendota) that will produce H_2 from wastewater. To enable this process, the company will construct additional tertiary water treatment plants to prepare wastewater for industrial use in H_2 production. This plant is scheduled for completion by 2025.[218] In addition to support H_2 production, such a project will contribute to improved wastewater management in local communities.

E-SAF



The use **of sustainable sources of CO_2** is essential to ensure a closed CO_2 cycle. This implies that only CO_2 that has previously been extracted from the atmosphere is used. Since DAC technologies are not yet fully scaled up, CO_2 from these sources is still costly. Further research and development is required in order provide sufficient quantities of sustainable CO_2 in the future. The use of biogenic CO_2 conflicts with the food industry and leads to competition for land and changes in land use, which is why these CO_2 sources are not available in the required quantities on a sustainable basis.[75] Airbus was awarded the German Future Prize in 2023 for the development of a DAC technology based on a technology that removes the CO_2 exhaled by astronauts on the International Space Station.[219] The continued development of innovative technologies will play a decisive role in the future production of E-SAF.

Various strategies should be considered to make efficient use of land for renewable energy production from photovoltaics (PV) and wind turbines while avoiding competition with food production.

According to published data[182], the area-specific yield for E-SAF in 2050 is 7,680 km to 19,930 km per hectare per year when using large-scale solar power plants and 3,770 km^2 to 6,860 km per hectare per year when using onshore wind farms. Combining these technologies enables a yield of 10,480 km to 24,480 km per hectare per year. Despite the higher gross area requirement for E-SAF produced based on electricity from PV systems (area coverage of 33%), compared with E-SAF based on electricity from wind systems (area coverage of 1.5%), the technology combination offers promising prospects due to the higher area-specific yield.

Agri-PV is another approach to overcoming the increasing space requirements for the construction of PV systems to produce E-SAF. This concept is based on the dual use of land and allows for the construction of large PV installations while keeping the land available for food production. Agri-PV is particularly advantageous in regions with nutrient-rich soil and a temperate climate, which are suitable both for agriculture and for PV systems due to high levels of solar radiation. In addition to increasing land use efficiency, agri-PV enables an increase in resilience and crop yields through technical adaptations to the systems. For example, the use of PV tracking systems can reduce irrigation requirements by 20%, collect rainwater for irrigation, reduce wind erosion and optimize light availability for plants.[187]

To identify suitable regions for E-SAF production, **feasibility studies** should generally be conducted to assess potential risks and develop minimization strategies. This early identification and mitigation of challenges and risks.

7.2.2. Social area (S) for SAF projects

1 | SAF general
The construction of SAF production facilities should contribute to the **creation of new jobs** that have a positive impact on socio-economic development at the local production site. Although no data is yet available on the jobs created by SAF projects so far, there are some promising developments.

In Port Colborne, Canada, Azure is planning a bio-based SAF project that, once successfully implemented, will create 1,500 construction jobs during the plant's construction and 150 full-time jobs during operation.[220] This SAF plant is expected to deliver approximately 3.18 million liters (2,521.74 tonnes) per day, with its first production in 2027.[221] LanzaTech, a pioneer in AtJ technology, is planning a project in the United Kingdom. With a capacity of 100 million liters (79,300 tonnes) per year, the project is expected to produce 150 full-time positions, including 85 skilled jobs on site.[222]

The HyKero project plans an E-SAF plant in Böhlen- Lippendorf near Leipzig with operations starting in 2027.[223] If successful, 100 jobs will be created directly in the plant itself and 500 more in accompanying service structures, such as maintenance, servicing and TÜV tests. HyKero is expected to produce 50,000 tonnes of SAF per year.[224]

The introduction of sustainable water management is a key element in **ensuring the supply of drinking water** and meeting other water needs of the local population in the context of SAF production. This is particularly important in regions affected by water stress (e.g., Middle East, north-east China, south-east Asia and southern West Africa). Effective water management is essential to protect human health and, at the same time, successfully implement SAF projects. Measures for sustainable and efficient water consumption must be implemented.

To make SAF projects successful, it is necessary **to integrate local and regional communities** and relevant actors and organizations. Cooperation based on trust makes it possible to address concerns early and take external perspectives into account. Cooperation with the local population can also raise awareness of the benefits of SAF. This not only promotes environmentally conscious behavior but also increases the acceptance of such projects.

The ICAO emphasizes that successful integration of the population can be achieved through a proactive, well-planned and strategic approach. Local stakeholders should be involved at an early stage and over the long term in order to build lasting trust. Transparent communication and inclusive, collaborative structures are key to this. A combination of new (e.g., social media) and traditional media should be used as a communication format.[222]

2 | Additionally for bio-based SAF

The health of the population can be significantly improved by implementing biological waste management systems that go hand in hand with the production of second or higher-generation Bio-SAF. Effective waste management not only contributes to the production of bio-based SAF but also creates healthier living conditions for local people.

Ensuring a secure food supply is another important aspect that can be achieved through sustainable cultivation methods and the careful selection of areas that do not compete with the food industry. By prioritizing land use that does not displace agricultural production, this approach helps to solve the "food vs. fuel" dilemma by ensuring that the production of biofuels is not at the expense of the food supply.

> We believe that fears of a shortage of raw materials are overrated as they are based on a static view. Biomass growth has already increased significantly due to the rise in atmospheric CO_2. This means that biomass is clearly scalable. There is also enormous additional production potential, for example, through algae growth, if a corresponding added value is possible as a result.

Dr. Mark Misselhorn, Chief Executive Officer, Caphenia GmbH

Precision agriculture also offers an approach to tackling the challenge of the conflict between feeding a growing world population and the increasing demand for sustainable energy and biofuels. It involves the use of advanced technologies to monitor and control plant growth and enables the optimized use of resources such as energy, water and fertilizers. In the USA, successes have been achieved in the integration of biofuels and precision agriculture. This enables farmers to predict crop residues that can be used for conversion into biofuels. In Brazil, precision agriculture is being used to maximize sugar cane growth and limit environmental impact through data-driven decisions.[225]

A promising approach for sustainable bio-based SAF production lies in the use of more sustainable raw materials, such as organic waste from agriculture and forestry, as well as plants grown on degraded lands that are not suitable for food or feed production.[226]

The lack of occupational health and safety in many sectors, including renewable fuels, is often overlooked. Bio-based SAF plants and commercialization projects should take account of SDG objective 3 (health and well-being). For example, when operating bio-based SAF plants, it is essential to minimize the release of harmful chemicals. The promotion of health in the workplace, including physical, mental and social well-being, is critical. To ensure occupational safety and protection and to prevent injuries, fatalities, and illnesses, reference can be made to the ISO 45001 standard. It aims to improve air quality, eliminate toxic substances, provide personal protective equipment for workers, implement organizational safety protocols, ensure access to clean water, use labeling and warning signs and provide supportive measures to promote mental health.[178]

3 | Investing in additional power generation facilities as part of E-SAF initiatives can help improve the local community's electricity supply. The projects must include both a capacity overbuild of renewable electricity and grid reinforcement.[75] It is also vital to make the E-SAF energy production process efficient to avoid potential conflicts with the local energy transition.[182]

7.2.3. Governance (G) for SAF Projects

1 | General governance
To fully exploit the potential of SAF, extensive regulatory measures are necessary. An essential factor in this regard is that financial support opportunities should be created. These can directly support existing and new production facilities and help establish favorable conditions for research and development in production technologies. This can significantly advance the expansion of SAF capacities.

> Incentive systems and tax benefits play a crucial role in promoting SAF. In the United States, for example, such mechanisms are already being used on a larger scale to support the production and use of alternative jet fuel.
>
> **Bernhard Dietrich,** Head of CENA Hessen, Hessen Trade & Invest GmbH

Additionally, abolishing subsidies for fossil fuels is generally seen as a significant regulatory measure to drive the decarbonization of the entire transport sector, including aviation.[190] Currently, the ramp-up of SAF production is hindered by high costs and the establishment of the necessary infrastructure. Furthermore, significant technological advancements are still required, necessitating financial resources. Governments can make a significant contribution by creating corresponding funding opportunities that enhance attractiveness and lower entry barriers to the SAF market. Other regulatory measures, such as tax incentives, can also create incentives.

Additionally, policies can be used to prioritize **renewable fuels** for those modes of transport that are difficult to decarbonize. This would favor the prioritization of SAF in production facilities, thereby maximizing production capacities.[189]

Establishing a **common regulatory framework** and implementing cross-border coordination and cooperation between countries is essential. This can prevent inter-sectoral competition from negatively impacting SAF production and avoid international incompatibilities that might hinder the effectiveness of national measures. Furthermore, the regulatory framework can create favorable conditions for market entry in the SAF sector. While regulations must be internationally coordinated and compatible, uniformity across all countries is not always advantageous. Instead, they should be tailored to specific economic and social contexts. Regional factors such as feedstock availability and renewable energy potential should also be considered.[189, 191] Some aspects, particularly accounting methods, should be standardized internationally to simplify trade and international activities typical in the aviation sector. Introducing SAF quotas, critical for aviation decarbonization, requires particular international coordination.

Gover
nance

This is important to prevent the relocation of company headquarters to countries with less stringent regulations, thus avoiding "carbon leakage."[189] The creation of such a common regulatory framework requires international cooperation with the objective of stimulating both demand and supply.[191]

A **constant and flexible adaptation** of existing regulations is necessary to achieve the smoothest possible ramp-up of the SAF application and simplify production and adaptation.[188] At the same time, the regulatory framework must be stable and reliable to give the parties involved the necessary planning security.[191] When finding new regulations, it is helpful to involve producers, buyers and other stakeholders to consider their needs and perspectives. This makes it possible to find advantageous solutions for all parties, such as simplifying cooperation between producers and buyers in supply contracts. Additionally, integrating the public and fostering understanding can also help facilitate an effective and efficient SAF policy.

2 | Governance bio-based SAF

One of the main challenges in the specific consideration of **bio-based SAF** is that land use conflicts and other negative effects in the procurement of the required biomass must be prevented. **Specifications on using biomass** as a raw material can play a role here. In the EU, for example, the RED II Directive prohibits the production of biofuels from biomass that could negatively impact land. This includes palm oil, the cultivation of which is often associated with the deforestation of rainforests. However, a holistic approach must be taken here. Banning only individual feedstocks could mean that the total land area is not reduced. Instead, substituting alternative crops, which require even more land, could even increase land use and the overall negative impact.[194]

It is also important to prevent the production of bio-based SAF from competing with the food supply when procuring biomass. This can be achieved, for example, through regulations that ensure that fewer food-grade plants are used for the production of biofuels.

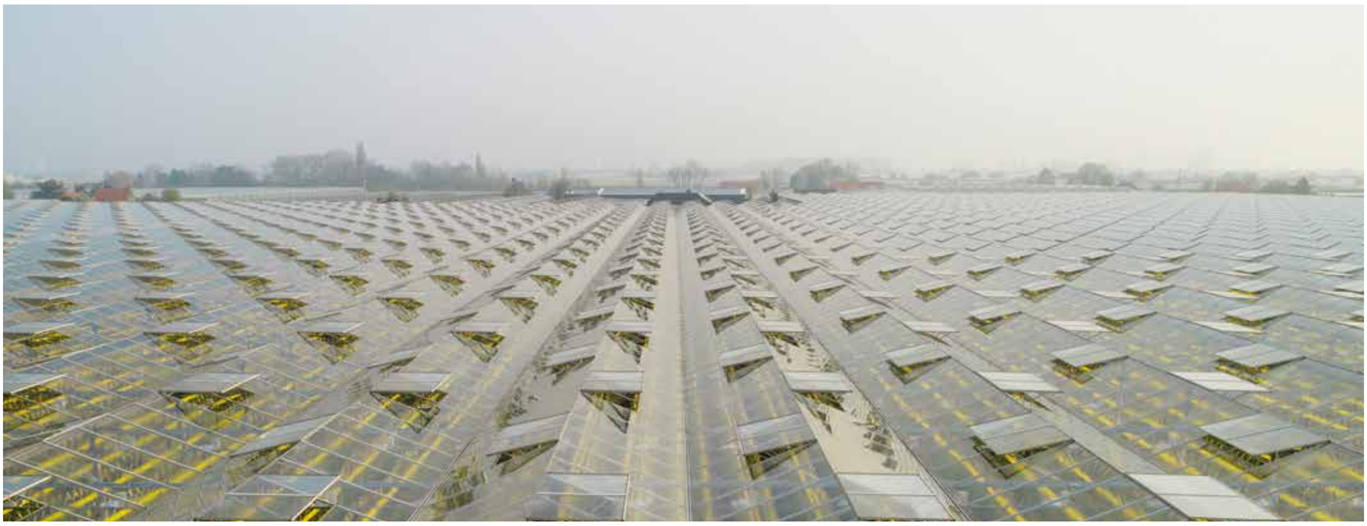
Among other things, incentives can be created to cultivate non-food crops on areas not fertile enough for food production.[192] Additionally, incentives should be established to utilize agricultural waste to produce biofuels. This approach could enable biofuel production in several regions and make it more cost-effective.[193]

With all these regulations, however, it must be noted that superficially positive requirements, which are intended to reduce the negative environmental impact of biomass procurement, for example, can have unintended consequences elsewhere. Moreover, banning certain biomass raw materials such as soybean oil may result in farmers in non-European growing regions such as Malaysia and Indonesia experiencing reduced demand and, consequently, lower incomes.[194] In addition, the availability of different raw materials must be carefully considered to strike an effective balance between economic efficiency, scalability and ecological and social sustainability.

Uniform regulations and sustainability certificates for bio-based raw materials are essential to ensure compliance with the measures described above. Only in this way can the potential of bio-based SAF to make aviation more sustainable be fully realized. For example, the need for robust and reliable certification processes is demonstrated by current developments in EU imports of biomass that can be used for SAF production. It is likely that palm oil is still in circulation since the ban on its use for fuel production falsely declared it as waste oil. For this reason, there are also calls for a standardized database to collect information on biofuels to increase transparency.[227]

The ISCC for SAF, which confirms the use of feedstocks with a low risk of negative land use impacts, already exists here on a voluntary basis.[196]

The cultivation of the raw materials required for bio-based SAF not only requires a lot of land but also high water consumption. Regulations on **sustainable irrigation management** can prevent the decarbonization of aviation from coming at the expense of other aspects of sustainability.[228] Examples of such regulatory measures are water pricing or allocation systems that limit the amount of water that can be taken from rivers. Various incentives can also be created for companies to use water more efficiently.[185]



3 | Governance E-SAF

To overcome obstacles to scaling E-SAF production, it is necessary to design regulations that **support the production and development of PtL technologies**. This is the only way to enable widespread commercialization.[182, 229] One possible measure is the formulation of sub-quotas that specify how much of the prescribed SAF share must have been produced using PtL. Such requirements exist in the EU, for example, as part of the RefuelEU-Aviation initiative. In addition, the provision of the necessary investments requires political support.

For example, regulations can create certainty for potential investors.[182] In particular, support for the development of DAC technologies is necessary in order to maximize E-SAF's decarbonization potential.

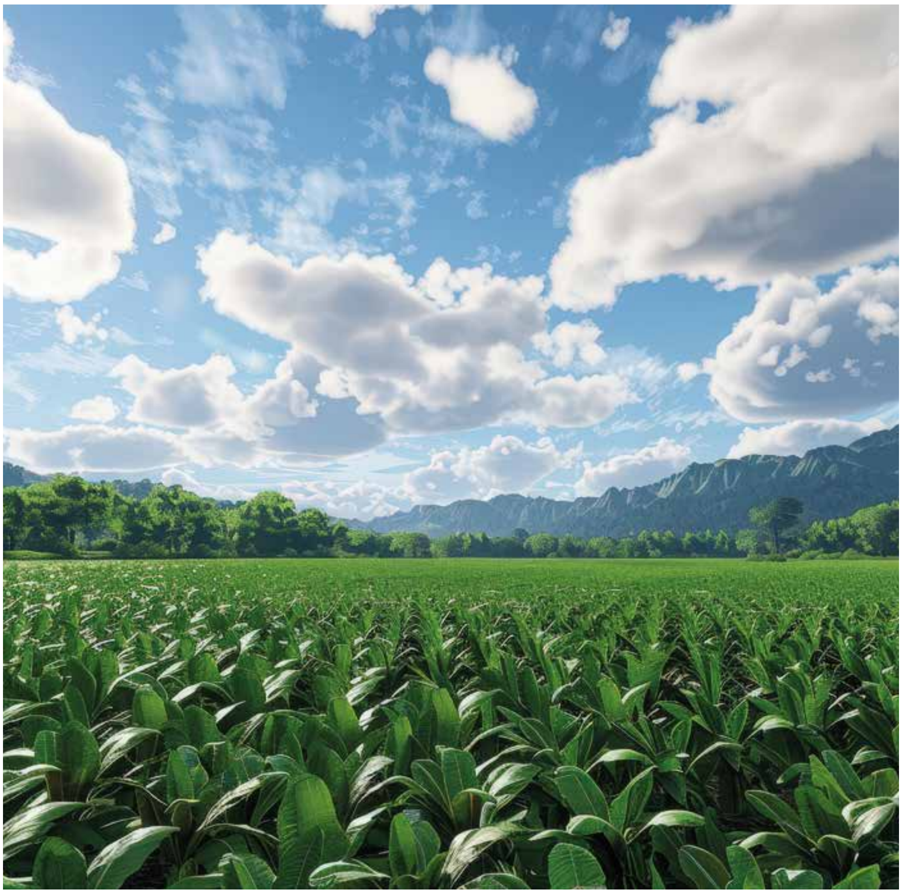
Carbon sources should be regulated to ensure the required CO_2 is obtained sustainably. This requires a regulatory framework that ensures CO_2 is directed toward hard-to-decarbonize sectors like aviation, given the limited availability of sustainable sources such as DAC.[197] As with the raw materials for Bio-SAF, uniform certifications for CO_2 and energy sources can also ensure that negative effects are prevented in E-SAF production.[196]

Creating **large-scale infrastructure systems** such as pipelines to transport CO_2 is also necessary to enable more location-independent industrial production.[197]

Furthermore, it has not yet been uniformly clarified how the CO_2 required in production is accounted for. Here, policymakers should create **internationally standardized accounting systems** and determine where this accounting will be carried out to avoid double counting.[197]

8

Critical EU success factors for the transformation of air transport



Introduction

A significant increase in demand for SAF has already been observed in recent years. The EY forecast discussed in Chapter 3 of this study indicates that this trend is expected to continue and even intensify in the coming decades. Currently, the entire volume of SAF produced is already being purchased with some customers experiencing difficulties acquiring SAF. Despite planned expansions of production capacities, a substantial supply gap is anticipated to develop in the coming years.

Particularly in the EU, where the market and demand are established by the ReFuelEU Aviation initiative, there is a critical need to close the gap between production capacity and market requirements.

There is a risk that many airlines will not meet the SAF quotas by 2030 and will have to pay high penalties. However, a greater challenge is expected from 2035, when the E-SAF quotas become relatively high. Investments must be made in development to mature the production technologies. E-SAF still requires significant advancements to reach industrial-scale production. At the same time, costs must be reduced to make SAF economically viable and commercially attractive for airlines. A combination of efficient and comprehensive political and financial instruments at the EU level should be achieved to create the conditions for successfully scaling SAF. The goal should be to advance the fulfillment of EU requirements.

In addition, conditions should be created for the SAF market to become attractive to both producers and buyers in the long term, even without subsidies and other support. Technology plays an important role here.

With this focus, the following chapter deals with the recommendations for regulatory, financial and technical framework conditions that can create optimal conditions for the bankability of SAF projects.

Success

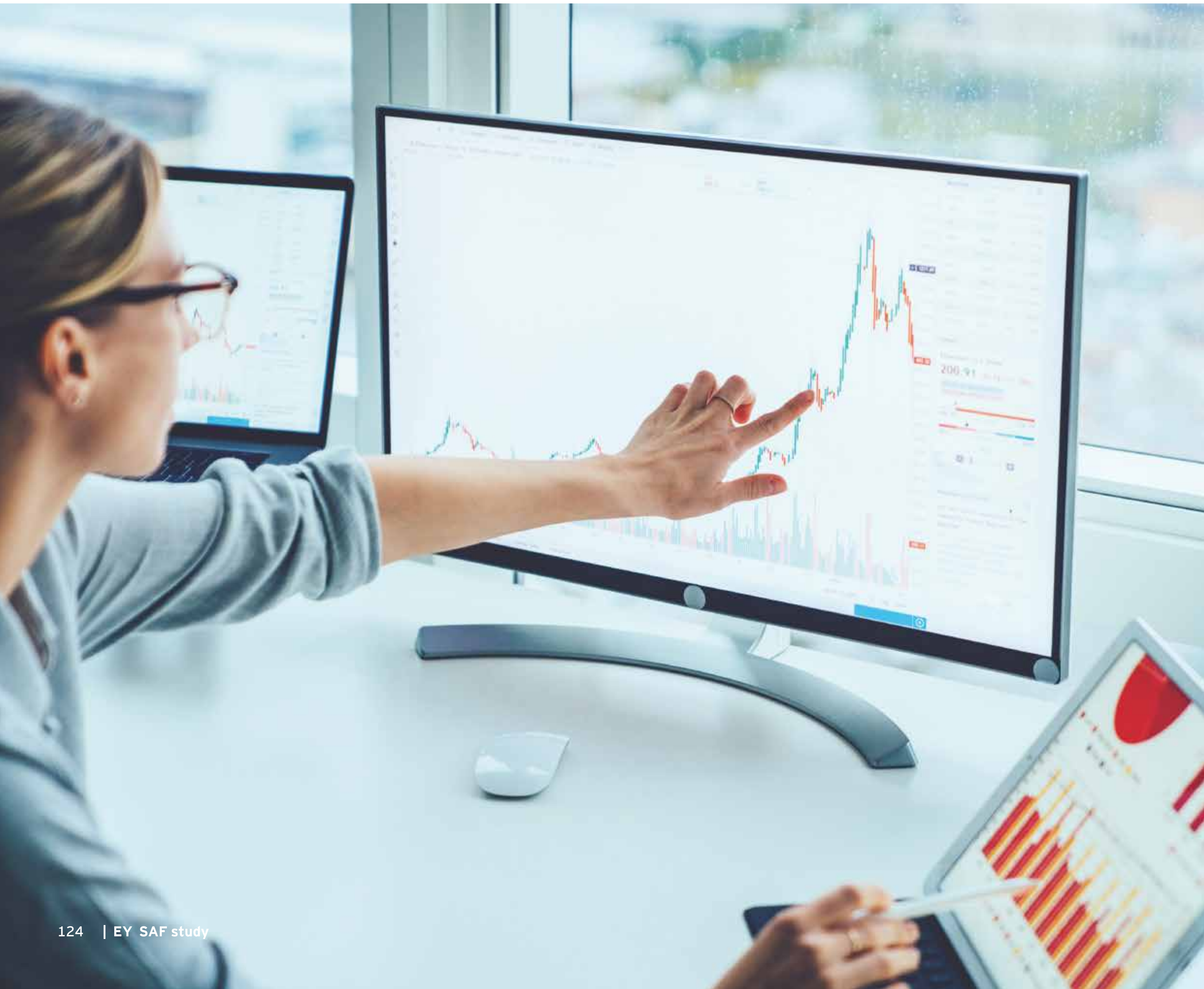
8.1 Development of financial instruments for SAF projects and improvement of financial viability

The availability of sufficient sources of funding is a key success factor. It is particularly important to provide public funding and combine it effectively with private capital. It will not be feasible to rely solely on private investors, as they have a return expectation of 11% to 20%, which is unrealistic in some cases.

There are already various sources of funding in the EU to support the decarbonization of aviation (e.g., funding for innovative production routes, H2Global). This also includes fines resulting from non-compliance with the ReFuelEU Aviation Regulation. These are collected centrally in each EU country and should generally be reinvested in the scaling of SAF. However, it is up to each country to decide how it uses these funds. It can then be difficult to allocate and prioritize the funds for SAF projects according to need. Collected fines should be centrally pooled to maximize effectiveness and efficiency.

This approach presents an opportunity to establish an EU-level fund dedicated to financing and promoting SAF projects, primarily within the EU. Such a fund could offer strategic advantages for both the EU and European airlines on a global scale.

The following section will describe the fund's structure, potential financial instruments and their respective function.



8.1.1. Overview of a possible fund and financial instruments

At the center of a possible EU fund should be an institution (possibly also European Hydrogen Bank – EHB) at EU level, which bears the central strategic and operational responsibility for the reinvestment of various financial resources in SAF projects. The EHB functions as a political instrument (within the framework of REPowerEU) aimed at boosting the production and promotion of green H_2.

However, there is potential to expand the main function of the EHB to support bio-based SAF and E-Fuel projects, especially when they are linked to H_2 technologies.

We see potential here for a possible addition of SAF, provided this does not conflict with EU regulation and/or applicable law.

The EHB currently has four pillars of activity, and a special SAF investment fund could be added to the fourth pillar.

This fund could consist of various sources of financing. Here, we propose five sources that can be used to finance SAF projects, but also for CfDs in the E-SAF area. Figure 48 provides an overview of all five financing sources and the entire mechanism.

Figure 47

Current structure of the EHB and proposed addition of SAF investment funds

(Source: EU, EY)

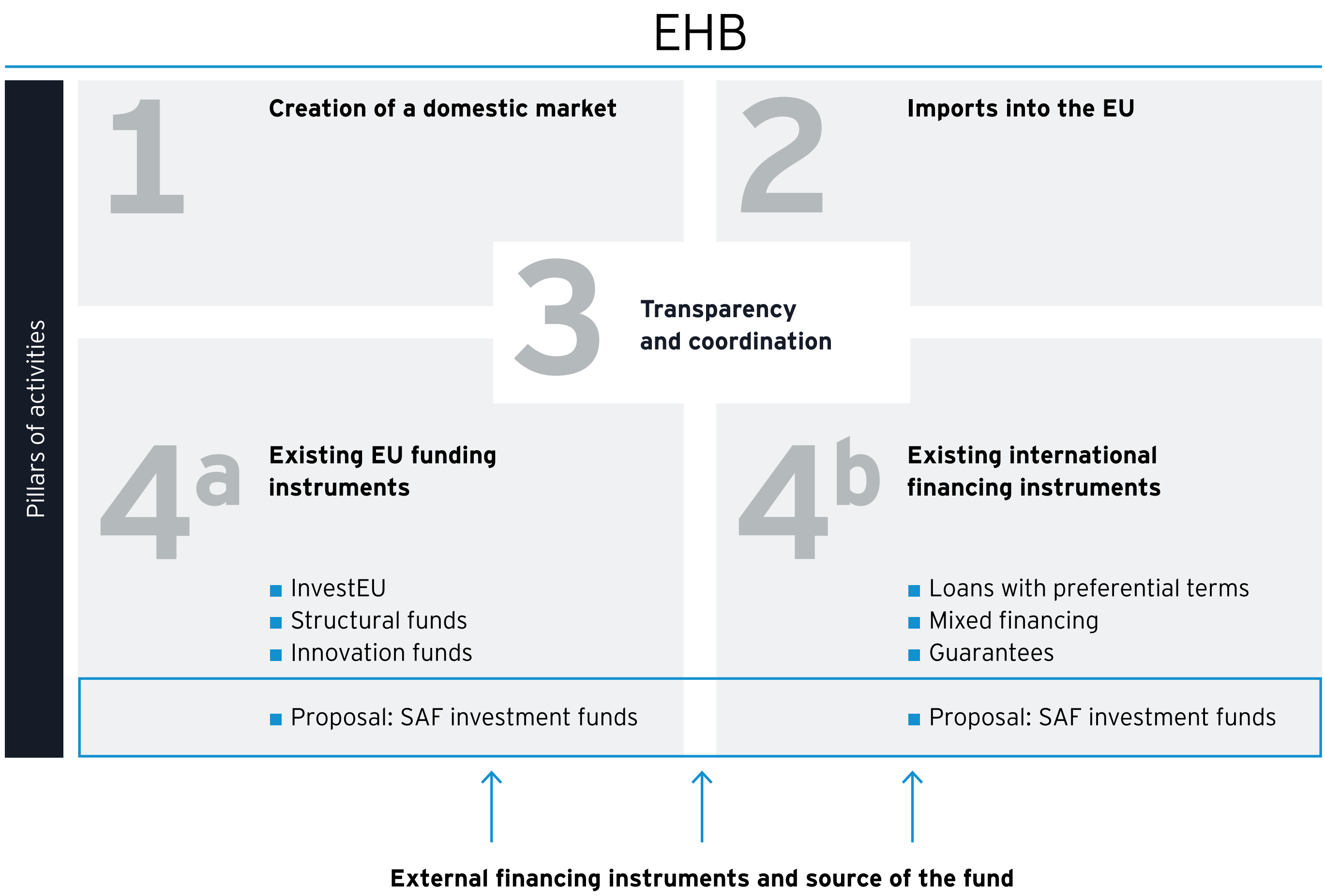
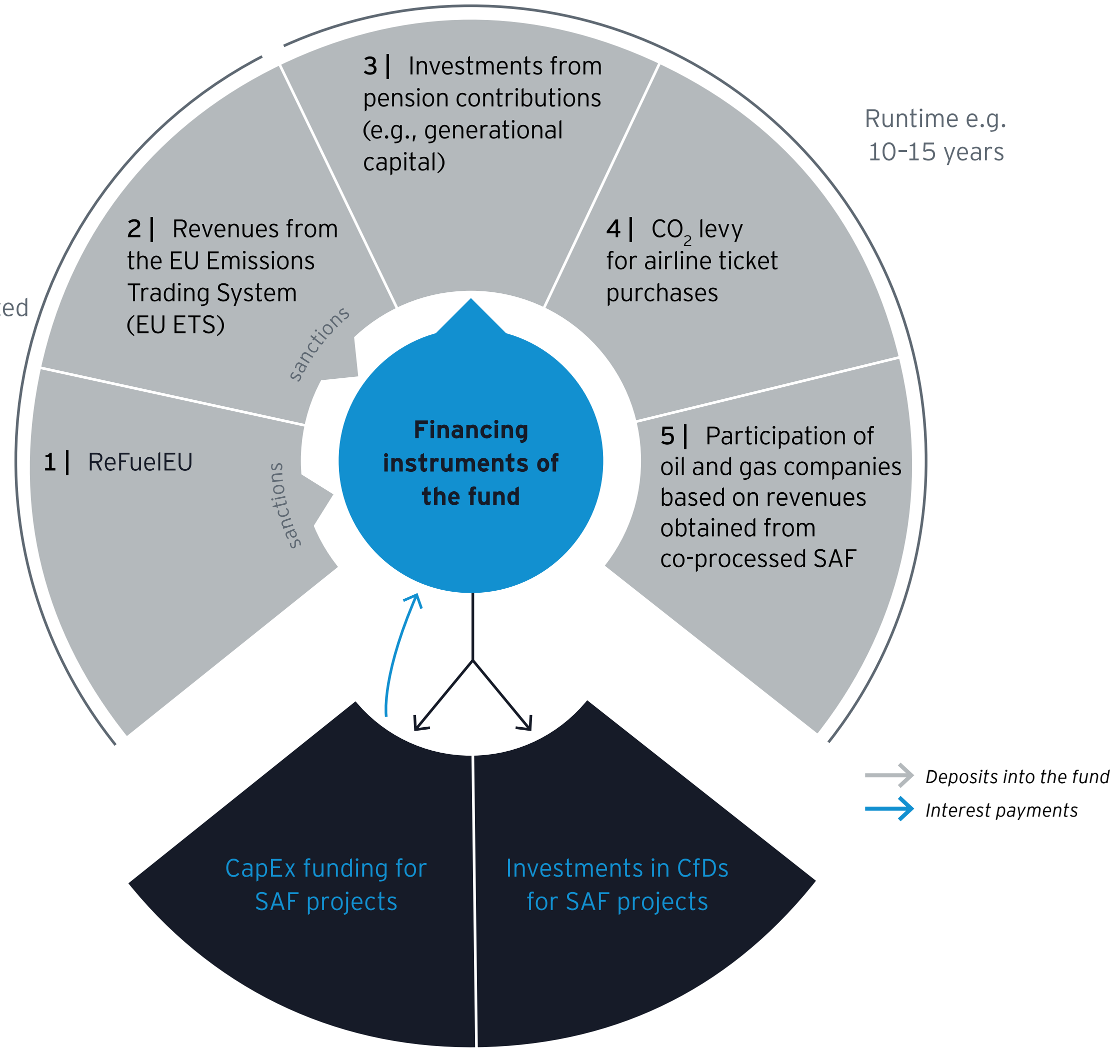


Figure 48

Overview of the model proposed by EY for providing financial resources for scaling SAF production

(Source: EY)



Financing

This includes both existing instruments that would only need to be bundled in their use by the fund, as well as newly proposed sources of financing. They include two existing mechanisms for which only a more direct centralized reinvestment in SAF scaling is proposed. These are fines for non-compliance with the ReFuelEU Aviation Directive and revenues from the EU ETS. In addition, four of the five sources are directly related to the aviation sector or the energy industry and thus ensure a direct redirection of financial flows towards low-carbon technologies.

1 | ReFuelEU aviation penalties: The regulation establishes SAF quotas for producers, airports and airlines. Non-compliance will incur penalties. However, the regulation does not yet specify who collects these penalty payments or how they will be used (reinvested). Currently, Member States are responsible for penalty collection and reinvestment. Although the regulation stipulates that investments must support the SAF industry, the precise implementation is left to individual Member States.[35] This system could be centralized, allowing financial resources to flow directly into a dedicated fund. Penalties would be individually determined by the Member States, subject to a minimum threshold. A central authority in each state could be responsible for collecting penalties and forwarding them to the fund.

2 | Proceeds from EU emissions trading: Similar to the ReFuelEU Regulation, the EU ETS also imposes targets on companies in the aviation industry. In this case, these are targets regarding their emissions for flights within the EU.[230] Maximum values are set, and if these are not met, payments are also due in the form of expenditure on emission allowances. Some of these certificates are auctioned directly by the EU Commission, others by the EU member states. Accordingly, revenues are distributed to the EU and to the member states. At both EU and national level, these revenues are allocated to funds for various purposes, primarily focused on climate protection.[231] Currently, for instance, all cross-sectoral German revenues from the ETS flow into the Climate and Transformation Fund.[232] In order to bundle the transformational power of these financial resources and maximize positive effects, the revenues from the aviation industry could also flow into the dedicated SAF fund. However, a transformation of the current allocation system for revenues from the ETS would be necessary for this. Currently, revenues are not separated by sector of origin.

3 | Investments from pension contributions: A novel funding source for the SAF sector could be investments from the Member States' pension systems that currently invest pension money in the stock market. The proposed fund would aggregate cash from pension contributions and make strategic investments in SAF development and production projects. The fund manager would conduct rigorous due diligence to identify suitable SAF projects, assessing technical feasibility, financial viability and environmental impact. The objective is to select projects promising both sustainable and profitable returns. Investments from pension contributions in SAF projects offer a win-win scenario: pension funds can achieve stable, long-term returns while simultaneously reducing CO_2 emissions and promoting sustainable technologies. However, such investments, require careful planning, comprehensive risk assessment and cooperation with government agencies and private entities.

For example, Germany recently introduced "generational capital," where a dedicated foundation invests in the capital market. The income generated is then used finance pension insurance.[233] These investments should be globally diversified to minimize risk; however, a focus on sustainable investments is possible, with a portion potentially flowing into a dedicated SAF fund. This approach would require reliable interest payments from the fund to the organizations managing the pension capital. Other EU countries with similar pension systems that invest in capital markets could also consider increased investment in sustainable opportunities like SAF projects. Countries such as Sweden and the Netherlands are particularly well-positioned to contribute to a dedicated SAF fund through their pension system.

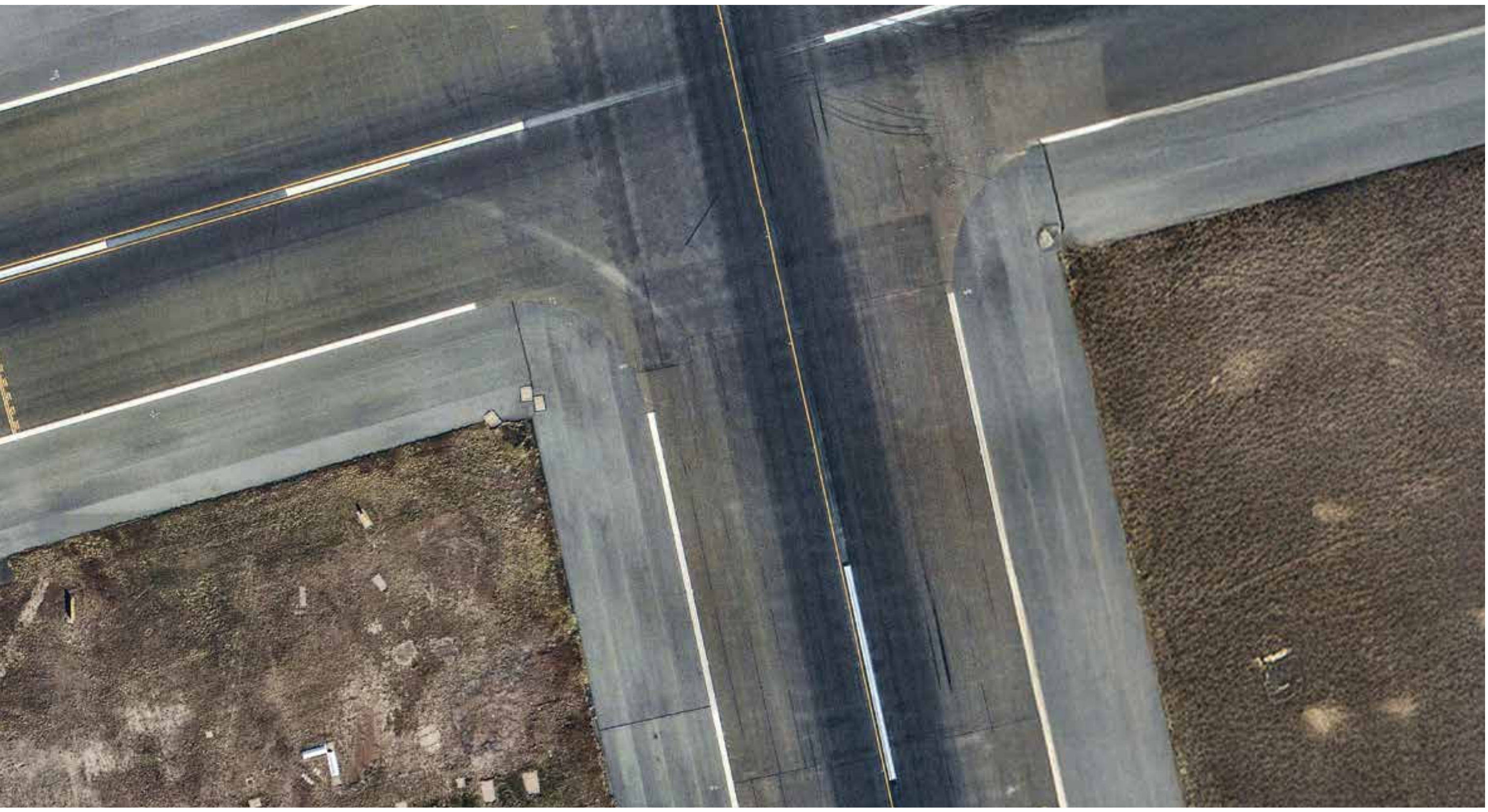
4 | CO_2 levy on air ticket purchases: Another potential revenue source for the fund could be a mandatory CO_2 levy on tickets for flights departing from or arriving at EU airports. This approach could build upon on existing voluntary contributions offered by many airlines. A flat-rate sum for European and foreign connections would be most practical, reducing operational complexity. A potential levy could be €5 (~US$5.4) for flights within the EU and EU10 to EU15 (~US$10.80–US$16.20) for flights abroad and international flights involving EU airports. Unlike traditional offsetting projects, these revenues would flow directly into the SAF project fund, ensuring a direct connection to aviation and supporting long-term improvements in the sector's climate impact. However, this instrument would require careful coordination with airlines.

5 | Tax on revenue from co-processing: Co-processing enables refineries producing fossil fuels to process biomass as a raw material alongside traditional fuels, directly producing SAF (e.g., HEFA). Existing plants can process biomass or waste with targeted adaptations and upgrades. In the EU, oil and gas companies operating such refineries may benefit from state subsidies to finance necessary plant conversions. Although co- processing can contribute to a significantly faster scaling of SAF production, this funding also entails risks. As retrofitting is significantly cheaper than building a completely new infrastructure to produce SAF, there is a risk that large energy companies will push smaller projects, such as startups, out of the market. To increase the financial resources available for investment in SAF projects and at the same time counteract this risk, the introduction of a new levy is an option. This levy could take the form of an additional tax on profits from SAF sales through co-processing. However, it is essential that this tax does not undermine the revenue potential from SAF's higher sales prices, ensuring SAF production remains economically attractive. Critically, the tax should only apply to SAF produced using the co-processing method, preserving maximum profit potential for pure SAF and redirecting money flows from fossil fuel-focused energy companies toward SAF production.

For the taxation of income from co-processing on national tax laws and regulations, companies must ensure that they calculate and pay all relevant taxes correctly and should inform themselves about possible tax benefits and incentives available for sustainable practices. In Germany, income from co-processing may be subject to the following:

- Corporation and trade tax
- Value-added tax (VAT) on SAF sales

Special regulations or incentives could exist for companies employing sustainable technologies and processes, potentially offered as tax concessions or support programs.



8.1.2 The function of the dedicated fund

All these resources should flow into the fund described above or the EHB (with an extended mandate) and be strategically reinvested in SAF production. The main advantage of such an approach is bundling the efforts to scale SAF production rather than Member States investing separately and with different approaches.

The investment priorities for this fund should focus on E-SAF. As discussed in section 6.3, this is where the greater potential lies in the long term. An important measure would be to use the fund to close the cost gap between SAF and fossil kerosene. Contracts for the difference could be a concrete means of achieving this. They are typically concluded between two parties to address price differences in traded products, and could be structured between E-SAF producers and the dedicated fund, potentially focusing on the price of green H_2.

Producers would receive funding from the fund to cover the price difference between green and gray H_2 required for E-SAF production. However, such direct benefits must not be the primary purpose or the sole use of the fund. Rather, the objective must be to make the production of SAF both economically viable and inherently attractive in the long term, even without regulatory intervention.

To make SAF — particularly e-SAF — economically attractive through market forces alone, targeted investments are needed in research and development, especially for PtL technologies. Advancing industrial-scale production also requires support for building production facilities and related infrastructure, which will help accelerate scaling and enable a steady increase in SAF output.

The dedicated fund for SAF projects, which is integrated into the EHB, has several essential functions to promote the development and implementation of SAF in Europe. Here are the main functions of the fund:

- Financing SAF initiatives, including providing funds for the development, construction and operation of SAF production facilities and awarding subsidies and grants to projects that use innovative and sustainable technologies
- Funding research and development projects that investigate and develop new technologies and processes to produce SAF; support of pilot projects aimed to demonstrate the technical feasibility and economic viability of new SAF technologies
- Financing infrastructure projects to support SAF production, storage and distribution networks; establishment and improvement of supply chains for raw material procurement
- Creating financial incentives to increase demand for SAF and promote investment in the SAF industry; provision of purchase guarantees and long-term purchase agreements to increase market stability and investment security
- Supporting international cooperation

By providing financial resources, supporting research and development, expanding infrastructure, creating market incentives, assisting with regulatory issues, capacity building and international cooperation, the fund significantly contributes to the development and spread of sustainable aviation fuels. This not only supports the decarbonization of aviation but also the achievement of the EU's climate targets.

8.2 Further possible technical development of SAF production

8.2.1 Production of bio-based SAF and co-processing of biomass

Bio-based SAF production routes are an available bridging technology to make enough SAF available as quickly as possible. In this way, the development of an infrastructure as well as the market ramp-up for SAF can be made both timely and recognizable for end customers. The market ramp-up of bio-based SAF should also facilitate the transition to E-SAF in the future, as both the infrastructure and business models are transferable. Furthermore, the marketing for Bio- and E-SAF could also seamlessly and flexibly interpose in terms of end customers.

As bio-based residues and sustainable biomass are limited, the players must coordinate their subjectively perceived ratio of opportunity to risk along the value chain. Specifically, their business models should be able to price in future increases in prices for raw materials, intermediate and end products and, ideally, react flexibly to market changes. One possibility for SAF manufacturers to be flexible is to be able to produce not only SAF, but also diesel and naphtha as feedstocks to produce sustainable plastics in various ratios to SAF.

This should be considered during the construction of new facilities but can also be achieved by expanding existing facilities from bio-based diesel, such as HVO, to Bio-SAF. For the stakeholders in the bio-based SAF value chain, who specialize in the distribution of residues and the production of sustainable biomass, it is similarly important to tap into additional markets, ideally those that already exist. On one hand, this involves marketing by-products, such as proteins from biomass cultivation; on the other hand, it includes exploring the market for sustainable raw materials, for example, oleochemicals for the chemical sector, such as industrial lubricants and cleaning agents.

Due to the limitation of raw materials, the period up to 2030 and the period after 2030 are considered separately below regarding technical developments and prioritization.

- **By 2030:**

By 2030, the HEFA and ATJ technologies will offer significant potential that will be realized during the current implementation and ramp-up phase. In the case of HEFA, the economically attractive valorization of the raw materials into HVO diesel and, in the case of ATJ, the direct use of alcohol as a gasoline additive still represent obstacles, at least for the time being. However, these obstacles should quickly turn into risk-mitigating factors, as the co-production of other fuel derivatives, such as ethanol, HVO diesel, or naphtha and LPG/propane, will also limit the risk of market ramp-up and improve SAF's bankability. In the end, market demand should be decisive for further development. With the adoption of the latest delegated act of RED II in April 2024, the basis was created for new raw materials to be reserved exclusively for Bio-SAF, such as HEFA and ATJ-SAF.[234] The simultaneous production of vegetable oils, sugars, residues and proteins from cover crops and their use for animal feed, bioenergy and biofuels could further enhance the business case for Bio-SAF. The gasoline and diesel fractions that arise as by-products in bio-based SAF production have been quantitatively restricted in the mentioned legislation.

The initial goal to maximize ATJ and HEFA production relative to ethanol (petrol) and HVO (diesel). However, if HEFA and ATJ demand fails to grow as anticipated, production would likely continue focusing on HVO and ethanol, with minimal bio-based SAF output. This could result in the global raw material potential for HEFA and ATJ – estimated at over 100 million tonnes in 2021 by Clean Skies for Tomorrow – remaining largely untapped for the EU.[235] The production of bio-based SAF requires less H_2 than E-SAF, which means that the market ramp-up by 2030 is not expected to be limited by the availability of green electricity for H_2 production.

Co-processing for SAF in refineries could significantly exceed the production of the existing HEFA/HVO stand-alone process routes in quantity. This enables a rapid scale-up of bio-based SAF by leveraging existing conventional refinery infrastructure.

- **From 2030:**

From 2030, the ATJ route will also increasingly be able to process synthesis gas, for example, from biomass gasification or waste gases from steel production. This opens up opportunities for hybrid bio/e-SAF synthesis, as syngas can also be utilized when CO_2 and H_2 are available for reaction. Additionally, methanol and ethanol can be combined in the production process, and certification of 100% SAF – featuring ATJ aromatics and eliminating the need for blending with fossil jet fuel – appears increasingly feasible. Co-processing in refineries could significantly boost E-SAF production volumes. Like the market ramp-up of bio-based SAF through co-processing, this approach could initially become the most economically attractive technological approach before dedicated E-SAF financially viable. Co-processing is also mentioned by the IATA as a method for the fastest possible market ramp-up.[236]

2030

Regulations for SAF and H_2 in the EU and at global level should be synchronized so that the market ramp-up for SAF and H_2 is not hindered regionally and globally on the one hand and does not lead to a regional or global trade imbalance on the other.[237, 238]

This is particularly relevant for regulations such as CORSIA, ReFuelEU, and RED II/III, as well as the emerging quota systems in APAC countries like China and Indonesia. Given that the APAC region is expected to drive the majority of future aviation growth, these regulatory frameworks will play a critical role in shaping SAF deployment.

In summary, developing and implementing bio-based SAF by 2030 and E-SAF from 2030 onwards are crucial for reducing greenhouse gas emissions in the aviation sector as quickly as possible. The use of co-processing in existing refineries offers a complementary approach to ramping up SAF production and initially promoting the sector's economic viability. In addition to CO_2 emissions, which are to be reduced by SAF, the so-called "non-CO_2 effects" of air traffic also have an impact on the climate.

These climate effects include nitrogen oxides, soot particles, oxidized sulfur compounds and water vapor released during flight. Condensation trails from water vapor and the resulting cirrus clouds are attributed significant influence, as explained further.

8.2.2 Improvement of non-CO_2 effects

In addition to CO_2 and water, aircraft engines emit nitrogen oxides, unburned hydrocarbons, soot particles and other substances when burning kerosene. At an altitude of 8 to 12 kilometers, the usual cruising altitude of most jet aircraft, the outside air temperatures can fall below −40 °C. When the hot, humid exhaust gases are expelled into this cold environment, they cool quickly, causing the water vapor to condense. The soot particles and other aerosols from the exhaust gases serve as condensation nuclei on which the water droplets can form.

Due to the low temperatures, the water droplets freeze immediately and form ice crystals. These spread out and form a visible trail behind the aircraft known as a condensation trail or contrail. Under cold and humid conditions, these streaks can persist for hours and spread out to form high clouds known as contrail cirrus.[239]

Depending on the sun's position, natural cloud cover and ground conditions, these artificially created clouds have a cooling or warming effect. They can reflect sunlight, producing a temperature-reducing effect, or retain heat radiated from the earth, causing warming. The precise effects of condensation trails, especially condensation trail cirrus, on the climate and surface temperature are still the subject of research. However, researchers broadly agree that, on a global average, the warming effect outweighs the thermal reflection.[240]

Aircraft engine emissions of nitrogen oxides, and sulphate and soot particles directly contribute to climate change.

Nitrogen oxide emissions promote ozone formation, which leads to a warming of the atmosphere. At the same time, simultaneously inducing methane decomposition that has a cooling effect. Sulphate particles reflect sunlight, thereby producing a cooling effect by preventing solar radiation from the atmosphere.[241] Conversely, soot particles can warm the atmosphere by absorbing sunlight.[242]

Manchester Metropolitan University and the DLR estimate that non-CO_2 effects account for most of the industry's impact on the climate. A full 2% of aviation's 3.5% share of man-made global warming is from non-CO_2 effects.[243]

SAF use can reduce the CO_2 effects and their climate impact, but also the non-CO_2 effects. SAF contains fewer soot particles and releases fewer greenhouse gases than fossil fuels, which reduces the formation of contrails and nitrogen oxide emissions.[244]

The quantification of the overall climate effects of using SAF is the subject of current research. Initial calculations estimate that the overall climate impact could be roughly halved by using 100% E-SAF.[245]

However, it is impossible to completely eliminate the non-CO_2 effects and their climate impact through SAF. Rather, further measures are required, such as optimizing flight routes or changing flight altitudes.

Abbreviations

ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
APAC	Asia-Pacific region
Bio-SAF	Biogenic Sustainable Aviation Fuels
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAGR	Compound Annual Growth Rate
CapEx	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
CCU	Carbon Capture and Utilization
CHJ	Catalytic Hydrothermolysis Jetfuel
CO	Carbon monoxide
CO_2	Carbon dioxide
CoA	Certificate of Analysis
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CST	Clean Skies for Tomorrow
DAC	Direct Air Capture
DLR	German Aerospace Center and space travel
DSHC	Direct Sugars to Hydrocarbons
EASA	European Aviation Security Agency
E-fuels	electrochemical fuels
EI	Energy Institute
E-SAF	Electrochemical Sustainable Aviation Fuels
EU ETS	European Emissions Trading System
EEA	European Economic Area
FAA	Federal Aviation Administration
FEED	Front-End Engineering Design
FFA	atty acids
FFP	Fit for Purpose
FT	Fischer-Tropsch
FTS	Fischer-Tropsch synthesis
GH_2	green hydrogen
H_2	hydrogen
HC-HEFA	Hydrocarbon Hydrogenated Esters and Fatty Acids
HEFA	Hydrogenated Esters and Fatty Acids
H_2O	water
HVO	Hydrogenated Vegetable Oils
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPO	Initial Public Offering
ISCC	International Sustainability & Carbon Certification
JIG	Joint Inspection Group
LCOE	Levelized Cost of Electricity
LPG	Liquified Petroleum Gas
O_2	Oxygen
OEM	Engine and aircraft manufacturers
OpEx	Operational Expenditures
PEM	Polymer electrolyte membrane
PtL	Power-to-Liquid
PV	Photovoltaics
RED	Renewable Energy Directive
RGGI	Regional Greenhouse Gas Initiative
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuels
SAFc	Sustainable Aviation Fuel Certificate
SDGs	Sustainable Development Goals
SIP	Synthesized Iso-Paraffins
SKA	Synthetic Kerosene Containing Aromatics
SOEC	Estoxide electrolysis
SPAC	Special Purpose Acquisition Company
SPK	Synthetic Paraffinic Kerosene
GHG	greenhouse gases
TNFD	Task force for nature-related financial information
TRL	Technology Readiness Level
UCO	Used Cooking Oil
WACC	Weighted Average Cost of Capital
WEF	World Economic Forum

List of tables

a Definition from ASTM D7566 for SPK: "synthesized paraffinic kerosine = synthetic blending component that is comprised essentially of iso kerosenes, normal kerosenes, and cycloparaffins", SPA:= SPK plus aromatics

List of illustrations

i It is important to emphasize that the projects mentioned in this context are only a selection of representative initiatives. It should also be noted that the transparency and visibility of funding initiatives may be lower in some regions than in others.
j The conversion from euros to US dollars is based on our EY pricing model. The conversion of country-specific currencies is carried out on the basis of the exchange rates at the time of publication of the projects.

Appendix

Appendix I: Detailed overview of funding sources

Table 13
Selective overview of global government support initiatives for SAF, e-fuels and biofuels, categorized by country and region (exemplary presentation, not a complete coverage of all support programs)

Country/ region	Project/ initiatives	Donor	Brief description and funding purpose	Announcement/ period of funding	Conveying volume
EU	SAF Fund	EU	As part of the ReFuelEU Aviation initiative, the SAF Fund (Amendment 86, Article 11a) was introduced. It is intended to contribute to the decarbonization of the aviation sector from 2030 to 2050. Special attention is given to promoting investments in innovative technologies and infrastructures. These include the production, introduction, use, and storage of SAF, alternative propulsion technologies for aircraft such as hydrogen and electricity, as well as research for new engines and technologies for direct CO_2 capture from the atmosphere. Additionally, measures to reduce the non-CO_2 impacts of aviation are to be supported. All investments funded by the SAF Fund will be made public and must align with the goals of this regulation.	2030–2050	Not specified
EU	Innovation Fund	ETS trading	The EU Innovation Fund is financed from the reinvested resources of the EU ETS. This fund sometimes supports projects for SAF as well as other innovations in the field of H_2 technology. As one of the world's most comprehensive funding programs for advanced low-carbon technologies, with an estimated total budget of €40 billion (~US$43.2 billion), the Innovation Fund supports various projects, such as the "HySkies" in Sweden, which is dedicated to the production and development of E- SAF.[247] In April 2024, the EU Commission announced the funding of seven projects in the field of renewable H_2, which will receive a total of almost €720 million (~US$777.6 million) from the Innovation Fund. This funding is provided in the context of the EU's Hydrogen Bank. These projects contribute to H_2 production within Europe and receive subsidies to compensate for the difference between the production costs and the market price, primarily by conventionally produced H_2. The subsidies are over 10 years, if production begins no later than five years after receipt of the subsidy.[248]	2020–2030	€40 billion
EU	EU Emissions Trading System (ETS)	EU	This support is provided in the context of ReFuelEU Aviation. To compensate for the price difference between SAF and conventional kerosene, SAF certificates worth €20 million (~US$21.6 million) are awarded to in the EU in the context of the ETS.[249]	2023–2030	€20 million (~US$21.6 million)

Country/ region	Project/ initiatives	Donor	Brief description and funding purpose	Announcement/ period of funding	Conveying volume
EU	IPCEI Hy2Move	ETS trading	The initiative transnational projects in Europe that contribute to the achievement of strategic European objectives and are funded accordingly. Within this framework, H_2 projects are being coordinated and driven by 22 EU states. These include projects such as Hy2Tech, Hy2Use and Hy2Infra.[250] The Hy2Use project is being supported by the EU Commission with up to €5.2 billion (~US$5.46 billion); in cooperation with 13 member states, Hy2Tech receives funding of €5.4 billion (US$5.67 billion) from 15 member states.[251, 246] In 2024, the EU Commission also announced that the Hy2Infra project would be supported by seven member states with a sum of €6.9 billion (~US$7.45 billion).[252] Another project (Hy2Move) is expected to be announced by the EU Commission in 2024 and will focus on hydrogen-based mobility.[253] The funding could potentially cover e-fuel projects, but this remains to be determined.	2024	€1.4 billion (~US$1.5 billion)
Switzerland	SWEET Program	Swiss Office Federal of Energy (SFOE)	The Swiss Energy Research for the Energy Transition (SWEET) funding program is an initiative of the Swiss Federal Office of Energy (SFOE) to implement Switzerland's Energy Strategy 2050. Funding is awarded through competitive calls for proposals.[254] In 2023, reFUel.ch (Renewable Fuels and Chemicals for Switzerland) received CHF15 million (~US$17 million[k]) in funding. The project's objective is to reduce the cost of sustainable fuels and platform chemicals, increasing the load flexibility of production facilities.[255]	2021–2032	Including CHF15 million (~US$17 millionk) for the promotion of the reFUel. ch SWEET project program
UK	Advanced Fuels Fund (AFF)	UK Department for Transport	The fund supports investments in private projects for SAF. At the end of 2022, the first five projects were funded with a total amount of £82.5 million (~US$101.9 million[l]). In November 2023, nine further projects were selected in the second round, each of which will receive £53 million.[256]	2022–2025	£82.5 million (~US$101.9 millioni) among others
Canada	Strategic Innovation Fund	Government of Canada	The Strategic Innovation Fund generally supports innovative projects that drive Canada's economy forward. In 2023, the Minister of Innovation, Science and Industry announced an investment package of C$350 million (~US$261.2 million[m]) with the objective of Canada's Initiative for Sustainable Aviation Technology (INSAT). These investments are designed to expand research and development, focusing on hybrid and alternative propulsion, aircraft architecture, transition to SAF and aircraft operations.[257]	2023	C$350 million (~US$261.2 millionm) among others
USA	Part of the Fueling Aviation's Sustainable Transition (FAST Grant Program)	US Federal Aviation	As part of the US Inflation Reduction Act (IRA), the US government has adopted an investment package that provides for the development of SAF. Projects seeking funding must include activities in the production, transportation, blending and storage of SAF. The US financial incentives form part of the overarching objective of achieving greenhouse gas neutrality in the US aviation sector by 2050.[258]	2023 ongoing	US$244.5 million

k The exchange rate used here for August 2023 is 1 US dollar = 0.88 Swiss francs.
l The exchange rate used here for 2022 is 1 US dollar = 0.81 British pounds.[283]
m The exchange rate used here for June 1, 2023 is 1 US dollar = 1.34 Canadian dollars.[284]

Country/ region	Project/ initiatives	Donor	Brief description and funding purpose	Announcement/ period of funding	Conveying volume
Brazil	PAISS-Program	Brazilian government	In Brazil, the PAISS program was in 2018 to promote biofuel and ethanol production. It includes support in the form of loans, equity investments and grants.[259]	2018	BRL200 million (~US$38 million)
Australia	Sustainable Aviation Funding Initiative	Australian Renewable Energy Agency (ARENA)	In Australia, Australian Renewable Energy Agency (ARENA) 30 million Australian dollars (~US$20.1 million[n]) in 2021 as part of the Sustainable Aviation Funding Initiative to promote the development of the SAF industry with the specific objective of advancing production technologies for SAF from domestic raw materials. The initiative has several core objectives: It aims to improve technology readiness, expand technical and commercial opportunities for the production of SAF from renewable resources in Australia, and expand industrial capacity for this forward-looking industry.[260]	2021	AUD30 million (~US$20.1 million[n])
China	Investment Plan of SPIC	State Power Investment Corporation (SPIC)	In China, the State Power Investment Corporation (SPIC), a state-owned enterprise under the administration of the Chinese central government, announced a US$5.85 billion investment plan for north-east China in 2023. The objective of this investment is to produce e-fuels based on wind energy. Together, the funded projects are expected to produce 400,000 tonnes of SAF per year.[261]	2023	US$5.85 billion
India	Pradhan Mantri JI-VAN Yojana	Indian government	In India, the National Biofuel Policy of 2018 promotes domestic production of sustainable fuels. A funding scheme of around INR50 billion (~US$728.8 million[o]) over a period of six years has been launched to bridge the funding gaps for 2G ethanol biorefineries.[262] Between 2018 to 2024, financial support of around INR19.695 billion (~US$287.1 million[p]) has been assured by the Indian government for setting up second- generation ethanol projects from renewable resources. This was done as part of the Pradhan-Mantri-JI-VAN program.[263]	2018–2024	INR16.9695 billion (~US$287.1 million[o])
Japan	Green Innovation Fund	Ministry of Economy, Trade and Industry (METI), Ministry of Land, Transport and Tourism (MLIT)	In Japan, the Ministry of Economy, Trade and Industry (METI), in cooperation with the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), plans to provide government support for research and development and operations in SAF production in 2023. This also promotes the acquisition of certification to strengthen the domestic production of SAF. A capital investment program is also planned.[264] In 2022, the "Green Innovation Fund", which supports innovative environmental projects with JPY2.3 trillion (~US$15 billion[p]), around JPY114.5 billion (~US$755 million[p]) has been earmarked for projects in the areas of e-fuels, SAF and sustainable fuels. In addition, METI, in cooperation with the New Energy and Industrial Technology Development Organization (NEDO), provided a further JPY5.18 billion (~US$34 million[p]) for the development of bio-jet fuel technologies.[265]	2022	JPY119.68 billion (~US$789 million[p])
Singapore	Aviation Sustainability Program	Civil Aviation Authority of Singapore (CAAS)	In Singapore, the Civil Aviation Authority of Singapore (CAAS) has signed the "Sustainable Air Hub Blueprint 2024," which provides measures for the promotion of SAF. The objective of the Aviation Sustainability Program 2023 is to support sustainable aviation projects. Around SGD50 million (~US$37.1 million[q]) will be made available to cover investment costs and accelerate industry-led projects.[266]	2023 ongoing	SGD50 million (~US$37.1 million[q])

n The exchange rate used here for July 2, 2023 is 1 US dollar = 1.49 Australian dollars.[285]
o The exchange rate used here for 2018 is 1 US dollar = 68.608 Indian rupees.[286]
p The exchange rate used here for July 2, 2024 is 1 US dollar = 160.9148 JPY.
q The exchange rate used here for 2024 is 1 US dollar = 1.3470 Singapore dollars.[287]

Country/ region	Project/ initiatives	Donor	Brief description and funding purpose	Announcement/ period of funding	Conveying volume
International /Africa	ICAO European Union Assistance Project	EU	Support for 10 African countries (Cape Verde, Senegal, Mali, Ivory Coast, Benin, Rwanda, Botswana, Zimbabwe, Seychelles and Madagascar) in the reduction of their CO_2 emissions in the aviation sector through production and distribution the implementation of government action plans, the development and implementation of savings opportunities and the introduction of CO_2 monitoring systems for the aviation sector (Aviation Environmental Systems, AES for short). However, it should be emphasized that the support provided under this project is limited to national governments and not specifically on individual industrial projects.[267]	Project phase II: 2019 until	€1.5 million (~US$1.7 million)[268]
International	Funding via ICAO-ACT-SAF	EU	In 2023, the European Commission announced financial support for the development of SAF as part of the "ICAO ACT SAF." The aim is to support a selection of partner countries with feasibility studies and the certification of these fuels. The project comprises twelve partner countries (Cameroon, Egypt, Equatorial Guinea, Ethiopia, Gabon, India, Kenya, Mauritania, Mozambique, Rwanda, Senegal and South Africa).[269] In total, the ICAO ACT SAF project, which was established in 2022, comprises 90 member states and 63 participating organizations. It enables states to further develop their potential in terms of SAF development and implementation.[270]	2023 ongoing	€4 million (~US$4.3 million)
Africa/ International	Africa-Europe Green Energy Program	Public and private actors from Africa and Europe	The program's objective is to increase energy production and improve overall access to energy sources by engaging public and private sector stakeholders in both Europe and Africa. It includes the following: ■ Optimizing energy efficiency ■ Development of regulatory reforms to create an investment-friendly climate ■ Promoting the integration of the energy markets ■ Increasing energy production ■ Improving access to energy sources One component of this project is, for example, the implementation of the Power-to-X reference network (P2X), which is specifically intended to strengthen Morocco's position in this sector. With funding of €110 million (US$109 million), the project is intended not only to attract private capital flows, but also to develop new technologies, contributing decisively to the development of a sustainable green H_2 economy in Morocco.[271] In line with the objectives of this initiative, the German Chancellor Olaf Scholz announced at the end of 2023 that Germany will increase its investments in green energy projects in Africa to €4 billion by 2030 (~US$4.32 billion).[272]	Not specified	et al. €110 million (US$109 million) for setting up a P2X-H_2 plant in Morocco

Sources of funding

Appendix II: Key assumptions for the calculations in Chapter 6

Overview of the basic premises for calculating E- and bio-based SAF
When calculating the LCO of E-SAF and Bio-SAF, further basic assumptions were made that apply across the board for both types of SAF and are listed and partially explained below.

Cost components and relevant data points	Definition of	Explanation
Operational lifetime of the facility	25 years (for all regions uniformly)	The typical operating life of E-SAF and bio-based SAF systems is 20 to 30 years.
Debt/Capital ratio	35% (for all regions uniformly)	The debt/capital ratio of 35% is the global average for corresponding quotas in the "chemicals" and "green and renewable energies" sectors according to publicly available data.[273]
Interest rate	3.5% (for all regions uniformly)	The interest rate of 3.5% is the global average interest rate in the following sectors "Chemicals" and "Green and renewable energies" according to publicly available data.[274]
Maintenance and Maintenance costs	3.5% of the original CapEx (for all regions uniform)	Assumption by EY.
Energy costs	It is expected that the LCOE from 2024 to Halved in real terms by 2050 become, above all due to the technological Improvements (for all regions different)	Electricity is for the production of E- and Bio-SAF. The electricity costs using of exclusively renewable energy sources were analyzed based on the concept of Levelized Cost of Electricity (LCOE). The primary data source is the Wood Mackenzie Reports.[275, 276, 277] The calculation of the LCOE was based the following assumptions: ■ The global electricity generation costs are based on the average electricity generation costs for the selected countries in the EU, the USA and the APAC region. ■ Taxes (property taxes, regulatory taxes, corporate taxes, other taxes) or statutory fees) are in the electricity generation costs. ■ Electricity from renewable energies is produced close to the plant where SAF is generated, eliminating transportation costs. Other region-specific assumptions: ■ **EU:** Subsidies, tax credits and incentives are included in the levelized cost of electricity for the EU are not included. It is assumed that these advantages will not exist in the long term. ■ **USA:** The tax credits for the USA are expected to continue until 2050, as the US electricity sector will not reach the 25% of CO_2 emissions by 2022 required for the expiry of the Investment Tax Credit (ITC) and the Production Tax Credit (PTC). are required under the Inflation Reduction Act. ■ **APAC:** Subsidies, tax credits and incentives are not in the LCOE for the APAC region. It is assumed that these benefits will not exist in the long term.

calculations

Cost components and relevant data points	Definition of	Explanation
Costs for green H_2	It is assumed that the costs for green H_2 will decrease due to the falling LCOE, the gradual reduction in CapEx over time (expected technological progress) and the increase in electrolyzer efficiency (different for all regions)	Green H_2 is essential for the production of E-SAF and to a much lesser extent for the production of bio-based SAF (see chapter 1.1 SAF types more details). The Levelized Cost of Hydrogen (LCOH) for H_2 was calculated using the water electrolysis method. Further assumptions made by EY: ■ **CapEx:** 1,500,000 US dollars/MW based on the average cost of alkaline and proton exchange membrane electrolyzers. ■ **The electrolysis stack,** which accounts for 45% of the original investment costs, will be replaced after twelve years. Due to the expected technological progress, a CapEx reduction factor is also taken into account (uniform for all regions). ■ **Maintenance and repair costs CapEx:** 3.5% of original CapEx; see above in this table (standardized for all regions). ■ **Service life of the system:** 25 years (standardized for all regions). ■ **Electricity costs:** See above in this table (different for all regions). ■ **Water costs:** Fixed at US$0.005/kg water with an annual adjustment of 2% due to increasing water demand[278] (uniform for all regions). ■ **OpEx:** OpEx includes maintenance, labor and other operating costs, which were set at 1.5% of the sum of CapEx and CapEx maintenance and repair costs (uniform for all regions). ■ **Insurance costs:** 0.5% of the original CapEx; see above in this table (standardized for all regions). ■ **Transportation costs:** not included; see below in this table (uniform for all regions). ■ **Taxes:** not included; see below in this table (standardized for all regions). ■ **Interest rate:** 3.5% (uniform for all regions). ■ **Plant capacity:** 100 MW ■ **Working hours of the system per year:** 7,884 hours (corresponds to 90% of the entire year). ■ **Electrolyzer efficiency:** increase from 65% in 2024 to 80% in 2050 (uniform for all regions). ■ **Profit margin:** not included due to direct internal reuse for the production of E-SAF and bio-based SAF (uniform for all regions).
Insurance costs	0.5% of the original CapEx (standardized for all regions)	Assumption by EY.
Transportation costs	Not included (standardized for all regions)	Transportation costs are not taken into account, as it is assumed that green H_2 is generated in the same plant where electricity and SAF are produced.
Taxes	Not included (standardized for all regions)	Taxes are not taken into account due to large local differences.

The calculations are based on real prices in 2023 and do not take inflation into account.

chapter 6

Detailed overview of further premises for calculating E-SAF

The levelized cost of E-SAF was calculated based on the methanol route. In addition to the assumptions already described, further assumptions specific to E-SAF were made, which are listed and explained below:

Cost components and relevant data points	Definition of	Explanation
CapEx	42,000,000 US dollars (for all regions uniform)	The CapEx for a plant with an annual production capacity of 100 MW was estimated at 420,000 US dollars/MW. Due to the expected technological progress a CapEx reduction factor is applied for future periods.
Maintenance and repair CapEx costs	3.5% of the original CapEx (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Electricity costs	See "Overview of the basic Premises for the invoice from E- and Bio-SAF" (for all regions different)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Costs for CO_2	The CO_2 costs were set at 864 US Dollar/ton fixed. (for all regions uniform)	The CO_2 costs are based on DAC technology (CO_2 from direct air capture). Due to the expected technological progress in DAC technology, the costs for A reduction factor is applied for future periods.
Costs for green H_2	See "Overview of the basic Premises for the invoice from E- and Bio-SAF" (for all regions different)	See "Overview of the basic premises for calculating E- and Bio-SAF".
OpEx	2.0% of the sum of CapEx and CapEx-Maintenance and repair maintenance costs (for all regions uniform)	OpEx includes maintenance, labor and other operating costs, which are estimated at 2.0%. The total of CapEx and CapEx maintenance and repair costs determined. The lower OpEx compared to bio-based SAF production (3.5%) is due to the lower number of of operations required in E-SAF production.
Insurance costs	0.5% of the original CapEx (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Transportation costs	not included (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Taxes	not included (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Interest	See "Overview of the basic Premises for the invoice from E- and Bio-SAF" (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".

Cost components and relevant data points	Definition of	Explanation
WACC	10% (standardized for all regions)	The higher risk associated with E-SAF production compared to bio-based SAF production and the resulting higher WACC are attributable to several factors: ■ The technology for producing E-SAF is relatively new and is still in the development phase. ■ SAF production requires considerable investment in infrastructure for renewable energies, electrolysis units and CO_2 capture technology. ■ There are considerable fluctuations the availability and cost of raw materials such as renewable energy and CO_2.
Production capacity and plant efficiency	100 MW/year (standardized for all regions)	■ Acceptance from EY. ■ Due to the technological progress assumed by EY, plant efficiency increases over the years.
Number of working per year	7,446 hours/year (standardized for all regions)	Assumption by EY.

Detailed overview of further premises for calculating bio-based SAF

The LCOH of bio-based SAF was calculated based on the HEFA route with UCO as the raw material used. The production process shown here with the respective quantity ratios applies to a production plant designed for HEFA-SAF as the main product, meaning the quantities of inputs and the type of production process are controlled in such a way that the largest possible proportion of HEFA is generated as the end product and the proportion of HVO diesel is lower compared to many existing plants today. The higher proportion of HEFA as an end product also means that the proportion of propane gas produced increases compared to an HVO diesel-oriented plant.

In order to the levelized cost of Bio-SAF, further assumptions specific to bio-based SAF were made in addition to those already described, which are listed and explained below:

Cost components and relevant data points	Definition of	Explanation
CapEx	677,000,000 US dollars (uniform for all regions)	The CapEx for a plant with an annual production capacity of 250,000 tonnes was calculated based on literature values and using the following formula regarding the relationship between the increase in CapEx and the increase in capacity (scale economies) with a coefficient of 0.6[279]: $$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^{\alpha}$$ *C_1: CapEx of bio-based SA Fproduction plant 1; C2: CapEx of bio-based SAF production plant 2; V_1: Capacity of bio-based SAF production plant 1; V2: Capacity of bio-based SAF production plant 2* *α: Scale coefficient; CapEx reduction factors are not taken into account due to the maturity of the production facilities.*
Maintenance and repair costs CapEx	3.5% of the original CapEx (standardized for all regions)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Energy costs	See "Overview of the basic premises for calculating E- and Bio-SAF" (different for all regions).	
Costs for biomethane to generate steam	~70 US dollars/MWh (uniform for all regions)	The production of HEFA requires the use of steam, whereby it is assumed for the underlying model that this steam is generated by burning gas, in particular biomethane, in order to be able to produce a product that is as environmentally friendly as possible compared to fossil gas. To obtain data for biomethane, the EEX futures for natural gas were used and a premium was added, as the prices for biomethane are usually higher, e.g., due to the lower economies of scale of biomethane compared to natural gas and sometimes higher production costs due to the pre-treatment of biomass to produce biomethane. Due to a lack of consistent data from a single source and to simplify the model, a globally uniform price for biomethane was chosen for all regions.

Cost components and relevant data points	Definition of	Explanation
Costs for certified Used Cooking Oil and Related raw materials	1,527 US dollars/Ton (for all regions uniform)	The costs for RED-certified used cooking oil and related raw materials (Jatropha, etc.) have been calculated based on the costs of rapeseed oil with a 50% markup. The costs of rapeseed oil serve as the baseline costs, as rapeseed oil has already been established in the market for 20 years as one of the most relevant raw materials for the production of biodiesel in the EU, with a scale of several million tons, produced and traded worldwide, thus providing reliable historical data that forms a good basis for further calculations. The 50% markup has been derived from the historically known price premium of UCO biodiesel over rapeseed biodiesel in the spot market in Northwestern Europe.[280] It is assumed that the price premium for oils based on cover crops and for plant oils produced on degraded land is in a very similar range. Since demand is regulated through regulations and blending quotas, the price structure will dynamically adjust through the market.[281] For future cost projections, the global agricultural raw material price index will be used.
Costs for green H_2	See "Overview of the basic premises for calculating E- and Bio-SAF" (different for all regions).	
Costs for alumina	1,210 US dollars/Ton (for all regions uniform)	This figure is based on the average cost per ton of alumina according to OFI Magazine (510–700 US dollars/tonne), i.e. 605 US dollars/tonne.[282] The costs were then doubled, as the requirements of the HVO in contrast to classic food and biodiesel oil purification are significantly higher according to the BDI.[283]
OpEx	3.5% of the total from CapEx and CapEx-Maintenance and repair maintenance costs (for all regions uniform)	OpEx includes maintenance, labor and other operating costs, which are estimated at 3.5%. The total of CapEx and CapEx maintenance and repair costs were determined. The higher OpEx compared to E-SAF production (2.0%) is due to the higher number of required in the production of bio-based SAF.
Insurance costs	not included (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Transportation costs	not included (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Taxes	not included (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
Interest	See "Overview of the basic premises for calculation of E- and Bio-SAF" (for all regions uniform)	See "Overview of the basic premises for calculating E- and Bio-SAF".
WACC	6% (for all regions uniform)	Assumption by EY.
Production capacity	250,000 tonnes/year (for all regions uniform)	Based on real data from a planned facility in Romania, an annual production capacity of 250 kilo-tons has been chosen.[284] This includes not only HEFA but also naphtha, HVO diesel, and propane as end products according to the production process (see above). The time interruptions due to maintenance, upkeep, and catalyst changes have already been taken into account.
Nickel catalysts	16.09 US dollars/ton used Raw material (for all regions uniformly)	Nickel catalysts are required in the production of HEFA for hydrotreating to accelerate the hydrogenation of vegetable oils or animal fats and to make the conversion into high-quality diesel fuels more efficient. Preferably, nickel-molybdenum catalysts are used. In co-processing, cobalt-molybdenum catalysts or mixtures of both catalysts are more commonly employed, as the O_2 content is relatively lower, and the sulfur content of the fossil component is usually much higher than that of the non-fossil component.

Appendix III: Research glossary

Alkenes	Branched, linear or cyclic unsaturated hydrocarbons which are not aromatic
Anthropogenic	Influenced or caused by humans
Aromatics	Aromatic compounds, ring-shaped molecules with double bonds, can occur in crude oil
Gasoline	Fuel boiling fraction in the refinery
Blending	Blending of fuel fractions, e.g., fossil fuel with sustainable aviation fuel
Biogenic Sustainable Aviation Fuels	Sustainable aviation fuels produced from biomass and biogenic residues be won
Biofuels	Sustainable fuels obtained from biomass and biogenic residues; overarching term for fuels for various means of transportation
Catalytic Hydrothermolysis Jetfuel	sustainable aviation fuel from used fats, oils and water
Cracking	Non-catalytic cracking of long-chain hydrocarbons with or without H_2 under high pressure and heat
Co-processing	Co-processing of Bio- and Fischer-Tropsch components with crude oil in the refinery
Cycloparaffins	ring-shaped saturated hydrocarbons
Deacidification	Deacidification of used or fresh vegetable oils
Degumming	Degumming of used or fresh vegetable oils
Diesel	Fuel fraction from the refinery, obtained by cracking, not necessarily standard-compliant diesel in the context of this study
E-fuels	Renewable electrochemical fuels from CO_2 and GH_2, overarching term for fuels for various means of transportation
Elastomer seals	Seals made from elastomers (molded and yet elastic plastics)
electrochemical Sustainable Aviation Fuels	electrochemical Sustainable Aviation Fuels, which are produced by processing CO_2 and GH_2 can be produced
Ethanol	Alcohol with two carbon atoms (drinkable)
Aviation fuel	Sub-type of fuel that is specially developed for aircraft propulsion, also called jet fuel
Fluid Catalytic Cracking	Catalytic cracking of heavy oil and diesel oil fractions without H_2
Fraction	Subgroup of substances in a mixture of substances, here e.g., various groups of fossil fuels obtained from crude oil
Fuel gas	Gas mixtures in the refinery that are thermally utilized
Gas Oil	Diesel fractions
green hydrogen	H_2 produced from renewable energy
Hydrogenated Vegetable Oils	green "hydrotreated" vegetable oil, premium diesel with high cetane number and a winter diesel blend component
Hydrogenation	Chemical reaction in which H_2 is added to other molecules
Hydrocracking	Catalytic cleavage of hydrocarbons with H_2, possibly with saturation of aromatics and isomerization of alkanes
Hydroprocessing	Combined process of hydrocracking and hydrotreating
Hydrotreating	Removal of heteroatoms (e.g., N_2, O_2) by means of hydrogenation and saturation of aromatics
Isomerization	Catalytic conversion of chain-like kerosenes to branched ones, so-called iso-paraffins

Jetfuel	Aircraft fuel (Jet-A1) according to global standard ASTM D1655
Kerosene	Boiling fraction in the range of jet fuel, but not always jet fuel
Fuel	Fuels whose chemical energy is converted by combustion into motive power for various means of transportation.
Liquified petroleum gas	Propane-butane mixture, also known as camping gas
Naphtha	Light gasoline, distilled from crude oil (straight run) or cracking product from various refinery processes such as cracking or by-product of SAF processes
Olefins	Unsaturated non-aromatic hydrocarbons, also known as alkenes
Paraffins	saturated hydrocarbons
Pentanol	Alcohol with five carbon atoms (not drinkable)
Petrol	Gasoline fraction
Pyrolysis oil	Oil that is produced from biomass (e.g., straw, wood) or plastic at high temperatures in the absence of oxygen
Reverse water	chemical reaction in which H_2O
Gas shift	(and CO as a by-product) is obtained from CO_2 and H_2
Synthesized	produced in a refinery process
Isoparaffins	Isoparaffins
SKA	SPK with aromatics
Synthetic Paraffinic Kerosene (SPK)	Mixture of synthetic kerosenes in kerosene quality, consisting of long-chain, branched and ring-shaped kerosenes
Synthesis gas	consisting of the gases CO, CO_2 and H_2
Workup	Processing of raw material or fuel fractions via distillation, Extraction or filtration etc.

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