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icarus

INTERNATIONAL COOPERATION FOR
SUSTAINABLE AVIATION BIOFUELS

Systemic constraints in the entire value chains: GAP analysis

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Dissemination level of this report	
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EXECUTIVE SUMMARY

The present report aims to provide a detailed evaluation of the current state and future potential of Sustainable Aviation Fuel (SAF) production technologies within the European Union and MIC countries. This report presents a critical analysis, to identify existing barriers and develop strategic solutions to enhance the SAF supply chain.

The report begins by examining the current status of SAF supply chains, detailing the involvement of various stakeholders, including biofuel producers, regulatory bodies, and market participants. It highlights the existing production pathways, such as Biocrude oils to SAF, Isobutanol to SAF, and Syngas to SAF, with a particular emphasis on the prevalent use of Hydroprocessed Esters and Fatty Acids (HEFA). Through a comprehensive SWOT analysis, the report identifies several weaknesses and challenges, such as feedstock availability disruptions and issues related to energy efficiency in SAF production.

The document further explores the desired future state of the SAF supply chain, setting ambitious goals and objectives aimed at fostering innovation and expansion in the sector. This future state envisions significant advancements in production capacities, the development of novel production pathways, and the diversification of feedstocks. The report underscores the importance of policy support and substantial investment to drive the widespread adoption of SAF. It emphasizes the need for increased collaboration among stakeholders, advocating for a unified approach to overcome the systemic constraints identified.

To bridge the gap between the current and desired future states, the report also outlines a detailed action plan. This plan includes recommendations for enhancing stakeholder collaboration, boosting research and development efforts, and promoting supportive policy frameworks. The goal is to establish a sustainable and scalable SAF value chain that can effectively reduce the carbon footprint of the aviation industry. The report calls for strategic investments in renewable energy infrastructure to meet the substantial energy requirements of SAF production. It also highlights the critical need for efficient water management practices to address the significant water usage in SAF production processes.

By identifying current barriers and proposing actionable strategies, the report aims to facilitate the development and adoption of SAF, contributing to global environmental goals and enhancing energy efficiency in aviation. The findings and recommendations presented in this report are crucial for policymakers, industry stakeholders, and researchers dedicated to advancing the sustainability of aviation fuels and achieving a greener future for the aviation industry.

This report concerns to Deliverable 1.6 of the ICARUS project.

Introduction

Due to increasing environmental concerns, the production of Sustainable Aviation Fuels (SAFs) has grown significantly. Many countries now have targets to replace fossil-based aviation fuels with renewable alternatives. This trend, coupled with the rising demand for air passenger transport and the growing number of aircraft orders, has necessitated a rapid expansion of SAF production.

SAFs represent a pivotal alternative to conventional jet fuel, offering the potential for a significant reduction in aviation's carbon footprint and a greater energy efficiency over conventional aviation fuel. Derived from non-petroleum feedstocks, which can include fats, waste oils, greases, green and municipal waste, agricultural waste and non-food crops, can be produced by biochemical or thermochemical routes.

The present project focus on technological improvements for 3 relevant pathways for SAF production such as Biocrude oils to SAF synthesis through Hydrothermal liquefaction (HTL), Alcohol-to-Jet (ATJ) using isobutanol as feedstock, and Syngas to SAF, through Fischer-Tropsch (FT) pathway.

The objective of this report is to perform a GAP analysis in SAF production, identifying constraints and disadvantages in the SAF value chain to create effective strategies to reduce or eliminate these failures and to achieve the proposed goals. To this end, three steps will be carried out, namely: (i) establishment and analysis of the current state of existing SAF production chains; (ii) defining the future state and goals for SAF supply chains and (iii) developing an action plan to mitigate the GAP between the current and future state, thus enabling the creation of solid business plans.

1. SAF: Evaluation of the current status of SAF supply chains

1.1. Key players in the SAF supply chains

The SAF value chain encompasses the entire lifecycle from feedstock, production, distribution, and delivery to his end use. The key players in the SAF supply chain include a range of stakeholders from different sectors like biofuel producers, airlines, airports, technology providers, feedstock providers, government regulation bodies, research institutions, investors, and financial institutions, non-governmental organizations, and certification bodies (Department of Energy, U.S., 2022). Figure 1 shows the SAF supply chain key players.

The SAF value chain is in its nascent stage and requires a collaborative effort among industry stakeholders, including producers, airlines, regulatory bodies, and governments, among others, to standardize practices, share risks, and create incentives. Investment in new technologies, policy advocacy, and forming global alliances are pivotal in overcoming these challenges and advancing the SAF supply chain towards a more sustainable future for aviation (Boing, 2023; ICF, 2020).

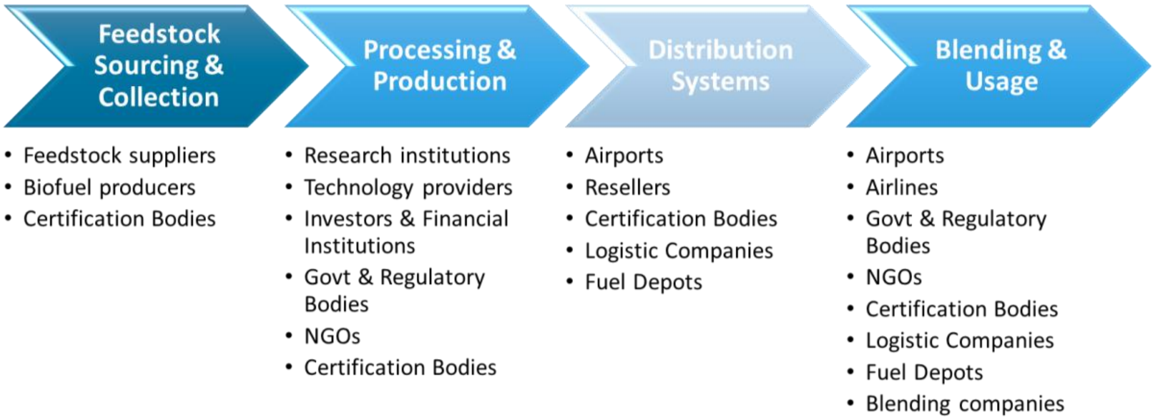

Figure 1 - SAF supply chain key players.

1.2. Evaluation the existing SAF supply chains

1.2.1. Feedstocks to SAF production

A wide range of feedstocks have been tested for SAF production, through different pathways. However, there are some key attributes that SAF raw materials must have. In addition to promoting a high yield of SAF, the raw materials used for SAF production must be cost-effective, not compete with food production and have a low environmental footprint (Lau, et al., 2024). Cover crops such as Camelina and *Brassica carinata*, cellulosic waste such as forestry, agricultural and wood residues, waste oil and fats, algae, municipal solid waste are some of the materials that have been used currently in the SAF production (Shahriar and Khanal, 2022). An overview of raw materials, associated pathways and those responsible for projects or commercialization proposals are present in Table 3. At the moment, HEFA is the most widely used route for SAF production, representing about 90% of total SAF production, using oil and fat raw materials (mainly palm, soy, rapeseed oils, used cooking oils and waste fats) (Ershov et al., 2023).

Table 3 - Overview of the feedstocks and associated pathways of SAF production (Shahriar and Khanal, 2022; Khalifa et al., 2024 and Firefly, 2024).

Feedstocks	SAF production route	Commercialization Projects/Proposals
Biomass-based feedstock (e.g. Agri-forest residues, municipal solid waste, etc)	Fischer-Tropsch (FT)	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Biomass, municipal solid waste (MSW), natural gas, coal	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SKA)	Sasol, Shell, Syntroleum, Velocys, Solena Fuels
Oil-based feedstock	Hydroprocessed esters and fatty acids (HEFA)	World Energy, Honeywell UOP,Neste Oil,Dynamic Fuels,EERC
Lignocellulosic biomass	Synthesized Iso-Paraffinic (SIP)	Amyris,Total

Ethanol, isobutanol, Lignocellulosic biomass or sugar-based feedstock	Alcohol-to-Jet (ATJ)	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
Algae, waste oil, oil plants	Catalytic Hydrothermolysis Jet Fuel (CHJ)	Applied Research Associates
Algae, moisture-rich feedstocks such as sewage, manure, and food processing waste	Hydrothermal upgrading (HTL)	Firefly

Figure 2 presents some of the main categories of raw materials globally identified by region, according to the study performed by Air Transport Action Group (ATAG, 2021). It is important to note that feedstock availability varies across regions, and this refers primarily to the technical potential of these raw materials, which reflects the total amount that could theoretically be used for SAF production. However, beyond just technical availability, it is crucial to prioritize the use of locally accessible feedstocks to maximize sustainability and efficiency. It is noted that the feedstock availability is different across the world, which must be taken into account, but not only. In addition to considering the opportunity in each type of raw material, it is important to favour the use of those raw materials available locally. Figure 2 also shows that the region with the greatest potential for raw materials is Asia-Pacific compared to other regions. As the SAF market in the Asia-Pacific is predicted to grow due to increase of low-cost airlines and rapid advancement of infrastructure, this large feedstock potential will be essential (Precedence Research, 2023). Europe has a slightly greater potential than that presented by Latin America & Caribbean and North America for the presented feedstocks. Africa and Middle East are the regions that present the lowest potential.

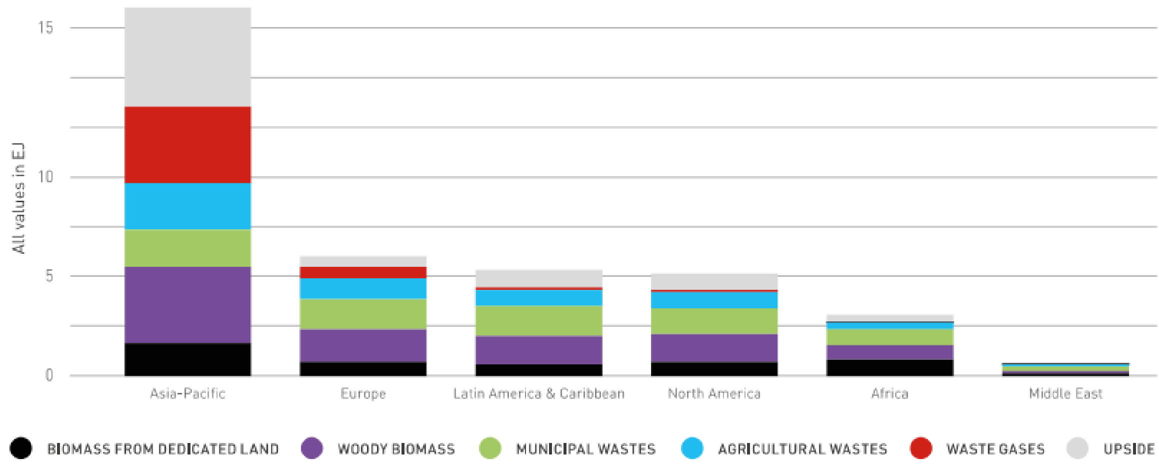

Figure 2 - Feedstocks availability in different regions [Transport Action Group, 2021].

According to a study supporting the impact assessment of the ReFuelEU Aviation initiative published in 2021 by the European Commission, the global SAF production capacity through the HEFA route using used cooking oils ranges between 7.8 and 10.1 megatonnes/year and for the EU between 2.3 and 3 megatonnes/year. These numbers can be higher if animal fats (tallow), oils from paper production, and residue streams from corn and palm oil production are also considered as feedstock. These feedstocks can also contribute to HEFA pathway increasing to 11-15 Mt of HEFA globally. In the ATJ and FT routes, agricultural and forestry residues can be used as feedstock. It is estimated that between 34 and 93 megatonnes/year of SAF can be produced in the EU from these routes using the raw materials mentioned above (European Commission, 2021). Nonetheless, although these feedstocks are abundant, and often widely used in other value chains, supply and availability are limited. The availability of feedstocks to these routes can be increased if in the future, since the agricultural sector may adopt the cultivation of lignocellulosic energy crops. Additionally, some routes involving gasification also use the organic fraction of municipal solid waste as a feedstock (European Commission, 2021). A lower production capacity of SAF can be expected using less developed production routes. However, these routes can be useful and cost-competitive when applied locally, using available feedstocks.

In the MIC countries participating in this consortium, there is a wide variety of raw materials that can be used in the production of SAF through different routes. Canada, for example, has an extensive forestry sector, which can provide forest residues to produce SAF. In addition, this country is a major global producer of canola. The target for harvesting this raw material in the country is to reach a total of 26 million tonnes by 2025. Canola, together with residual fats and greases, has great potential to be used as a raw material in the production of SAF through the HEFA route (GreenAir News, 2022). In Brazil, there is a wide variety of feedstocks that can be used in the production of AFS, namely oilseed crops, sugar and starch crops, algae, agricultural residues, forestry residues, cooking oils, municipal solid waste, flue gas and tallow. Brazil has a strong accumulated knowledge in the cultivation of sugarcane and oilseeds (soybean, rapeseed, palm, etc.), which can be used as feedstock in the production of SAF through the ATJ and HEFA routes, respectively. Also, the recent expansion of corn ethanol production in the Midwest holds strong potential for contributing for SAF production in the near future (Walter et al., 2021). Crops such as Jatropha, camelina and energy cane, which do not compete directly with food, can also be grown in Brazil, due to the country's climate. In addition to the raw materials mentioned above, residues from agricultural and forestry production (mostly eucalyptus), and co-products such as sugar cane bagasse and straw, are available in large quantities in the country. Combustion gas, urban solid waste, cooking oil and sewage are also abundant in Brazil due to the country's high population and have great potential for use as raw materials in the production of SAF (Cortez, 2014; IRENA, 2016). In India, abundant amounts of agricultural waste (agricultural by-products such as husks and straw), used cooking oil and other solid waste are generated. It is estimated that the 166 million tonnes of raw materials produced in India every year can be converted into 22 to 24 million tonnes of SAFs (McKinsey & Company, 2021).

Anyway, although there is currently a great potential for feedstocks globally, great attention needs to be paid to issues such as the availability of raw materials and seasonality of some biomass raw materials, such as agricultural residues and energy crops, since these barriers may limit the expansion of SAF production in the future, given that the SAF industry is growing.

1.2.2. Pathways of SAF production

There are several pathways for SAF production, some of which are already produced on a commercial scale. Figure 3 summarizes several routes for SAF production.

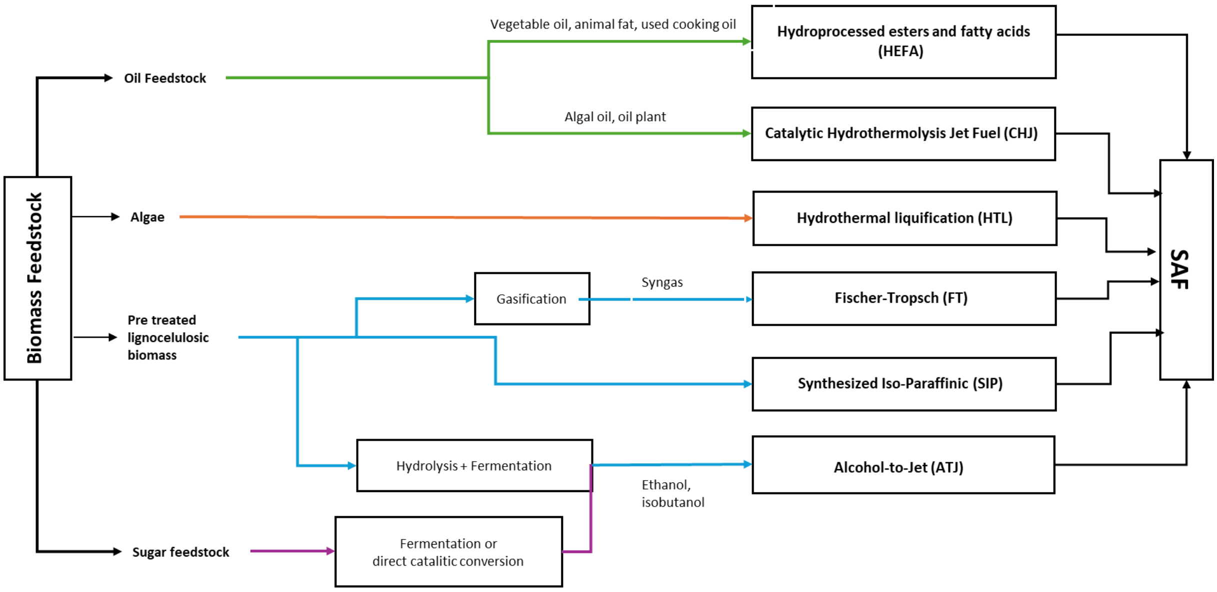

Figure 3 - SAF production pathways.

Some SAF production technologies are well-established, while others are relatively in the early stage and require further improvements. Currently, ASTM International (American Society for Testing and Materials) is responsible for certifying the SAF conversion process and the permissible blending ratio with conventional jet fuel. Due to their properties, certified SAFs can be blended with kerosene and used in kerosene-powered aircraft. Today there are eleven routes approved by ASTM International for SAF production, each with different blend limitations and Technology Readiness Level (TRL), as presented in Table 4.

Table 4 - SAF conversion technologies certified by ASTM international (Shahriar and Khanal, (2022); EASA, (2022); ICAO, (2024)).

ASTM Reference	Process conversion	Approved On	TRL[1]	Maximum Blend Ratio
ASTM D7566 Annex A1	**FT**	September 2009	7-8	50%
ASTM D7566 Annex A2	**HEFA**	June 2011	9	50%
ASTM D7566 Annex A3	**SIP**	June 2014	5	10%
ASTM D7566 Annex A4	**FT-SKA**	November 2015	6-7	50%
ASTM D7566 Annex A5	Alcohol (Isobutanol) to Jet Synthetic Paraffinic kerosene Alcohol (Ethanol) to Jet Synthetic Paraffinic kerosene **(ATJ-SPK)**	April 2016 April 2018	6-7	50%
ASTM D7566 Annex A6	**CHJ**	February 2020	6	50%
ASTM D7566 Annex A7	Synthesized Paraffinic kerosene from Hydrocarbon -Hydroprocessed	May 2020	4	10%

	Esters and Fatty Acids **(HC-HEFA-SPK)**			
ASTM D7566 Annex A8	Alcohol to jet-Synthetic Paraffinic Kerosene with Aromatics **(ATJ-SKA)**	May 2020	7-8	50%
ASTM D1655 Annex A1	**FT Co-processing**	May 2020	6-7	5%
ASTM D16557 Annex A1	Fats, Oils and Grease Co-processing **(FOG Co-processing)**	April 2018	7-8	5%
ASTM D1655 Annex A1	**HEFA Co-processing**	-	9	10%

[1] Technology Readiness Level Scale: (1-3) Research; (4-5) Prototype (6-7) Demonstration; (8-9) Ready for commercialisation (adapted from IRENA, 2016).

Another eleven conversion processes are currently under evaluation by ASTM, namely Synthesized aromatic kerosene, Integrated hydropyrolysis and hydroconversion, Single Reactor HEFA (Drop-in Liquid Sustainable Aviation and Automotive Fuel), Pyrolysis of non-recyclable plastics, Co-processing of pyrolysis oil from used tires, Methanol to jet, Increase in fatty acid/ester co-processing from 5% to 30%, HEFA with higher cycloparaffins, Biomass pyrolysis, Biomass/Waste pyrolysis and Cycloalkanes from Ethanol (ICAO, 2024).

Of the routes proposed in the ICARUS project, only the Syngas to SAF and ATJ using isobutanol are certified. The Biocrude oils to SAF synthesis pathway is still under approval. The main stages of the 3 routes proposed in this project will be described below. Furthermore, to better understand the current state of SAF production, the most established conversion processes and other potentially attractive routes will also be briefly presented.

In the syngas to SAF pathway uses the gasification process which the carbon-rich biomass is converted into syngas, that mainly consists of carbon monoxide (CO) and hydrogen (H_2). The process usually occurs under high pressure and temperatures. Syngas is then converted to SAF via Fischer-Tropsch catalysis (Khalifa et al., 2024; Ahmad et al., 2021). A wide range of raw materials including agricultural and forest waste, municipal solid waste and energy crops can be used as feedstock, which have very low carbon intensity (Ahmad et al., 2021). Some challenges of this pathway are very high CAPEX, complexity of syngas cleanup, relatively low yields and obtaining FT liquids requires additional processing (Khalifa et al., 2024). Several commercial-scale biomass gasification plants are in operation but for other end uses (e.g., power production), or under construction.

In the Alcohol-to-Jet (ATJ) pathway, alcohols such as ethanol, isobutanol and methanol or n-butanol are catalytically converted into long-chain hydrocarbons (Ahmad et al., 2021; Wei et al., 2019). However, only ethanol and isobutanol have been approved by ASTM. The use of ethanol as feedstock presents some advantages over others alcohol since the production of this alcohol has a very established technology, it is available at large scale and relatively low cost (first generation ethanol). This process consists of four steps: (i) dehydration, (ii) oligomerization, (iii) hydrogenation and (iv) distillation (Ahmad et al., 2021). This route presents relatively low CAPEX and high yield. One of the challenges of this route is the low availability and price of second-generation and advanced alcohols.

In the biocrude oil to SAF, wet feedstocks are converted into a bio-crude through hydrothermal liquefaction (HTL) at elevated temperature (250-550ºC) and pressures (5-25MPa). As the biocrude contains oxygen, the hydrodeoxygenation step requirement is necessary (De Jong, et al., 2017). The main products from this route are bio-crude, char, an aqueous steam containing water-soluble substances, and gas (predominantly CO_2 and CO) (IRENA, 2016). Although HTL biocrude contains less oxygen than the pyrolysis bio-oil, it still presents in significant amounts. So, this pathway presents some challenges to need overcome high oxygen content, high nitrogen content for some feedstocks, low pH, high hydrogen requirement for upgrading and high aromatics. There are very few pilot projects and no commercial facilities of the HTL process, but significant research in SAF production from sludge using this route is being carried out.

Most SAF currently in production is through the HEFA process, as this represents the most-cost efficient and mature pathway. In the HEFA route the SAF is produced using any type of oil, such as animal fat, waste grease, vegetable oil, or algal as feedstock. First, these oleaginous raw materials are hydrogenated and then, isomerized to produce long-chain hydrocarbons. Finally, an additional selective cracking process yields renewable aviation fuel (Ahmad et al., 2021). The industry faces challenges with feedstock supply constraints due to competition with the renewable diesel industry. Furthermore, the high cost of feedstocks, limited availability of waste feedstock and low quality of feedstocks are challenges that need to be overcome. As advantages, Hydroprocessed SAF has high energy content and is thermally stable (Ahmad et al., 2021; Strategy&, 2023).

Feedstocks such as jatropha oil, carinata oil, camelina oil, tung oil and waste oil can be used for SAF production through Catalytic Hydrothermolysis Jet Fuel (CHJ). The CHJ pathway can be divided into three major stages, pretreatment, CHJ conversion, and post-refining. The CHJ process corresponds of catalytic decarboxylation and dehydration steps at high temperature (250 to 380 °C) and a pressure (5 MPa to 30 MPa). After the whole process, are obtained naphtha, diesel, and SAF as products. (Shahriar and Khanal, 2022).

Synthesized Iso-Paraffinic (SIP), also known as Direct Sugar to Hydrocarbons (DSHC) or Direct Fermentation of Sugar to Jet (DFSTJ), generally uses sugar cane, beet, and maize as feedstock which are more abundant in some MIC countries (Brazil, India, US and Canada) than in Europe. This pathway commonly utilizes modified yeast to ferment sugars into farnesene (C15H24), that can be transformed into products, such as renewable jet fuel and diesel (Shahriar and Khanal, 2022).

Other current routes include pyrolysis, lignin to jet, power-to-liquids (PtL) and co-processing process. Pyrolysis is a process where thermal decomposition of biomass in the absence of oxygen produces a bio-oil that can be upgraded to jet fuel (Ahmad et al., 2021; Tanzil et al., 2021). In general, any dry biomass feedstock can be used in this process. However, the composition of the feedstock will interfere the yield and composition of the bio-oil. The pyrolysis route to SAF production is under evaluation for ASTM certification. Lignin to jet technology in turn, is still in development and has not been certified by ASTM. In this route, lignin extraction from lignocellulosic biomass is the first step. Next, the products are then depolymerized through fast pyrolysis, hydrogenolysis, or hydrolysis. Finally, the products go through fractionation to produce jet fuel (Shahriar and Khanal, 2022). PtL process does not require biobased feedstock. In the PtL pathway, green hydrogen from electrolysis, and CO_2 from renewable sources, is converted into SAF and other products though via FT or methanol synthesis (Braun et al., 2024; Strategy&, 2023). This route promotes high emission reductions of CO_2 when direct air capture is used. However, only part of the pathway is commercially established. As disadvantages, PtL process present high demand for renewable electricity, several fuel products and high production cost (Braun et al., 2024). However, it is believed that PtL is one of the most promising routes in the future (Rojas-Michaga et al., 2023). Lastly, the co-processing process is not in itself a SAF-centric production route, but rather the result of approving the use of a small percentage of vegetable oils, or FT waxes, in a refinery. In this process, vegetable oils as well as waste oils and fats, or FT waxes, are processed in existing refining complexes together with crude oil feedstocks (SKYNRG, 2024).

1.2.3. SAF regulations in Europe and MIC Countries

There is currently a huge diversity of initiatives, strategies and policies to stimulate the production and consumption of SAF around the world. Policies and regulatory frameworks play a crucial role in shaping the future of SAF supply chains. The increasing focus on reducing carbon emissions in the aviation sector has led governments to provide substantial support and incentives for sustainable aviation fuel (SAF) production and adoption as shown in Figure 4. These incentives include tax credits, grants, subsidies, and regulatory frameworks that encourage the use of SAF. Such government initiatives present significant opportunities for companies to invest in SAF production and benefit from the financial incentives and market advantages.

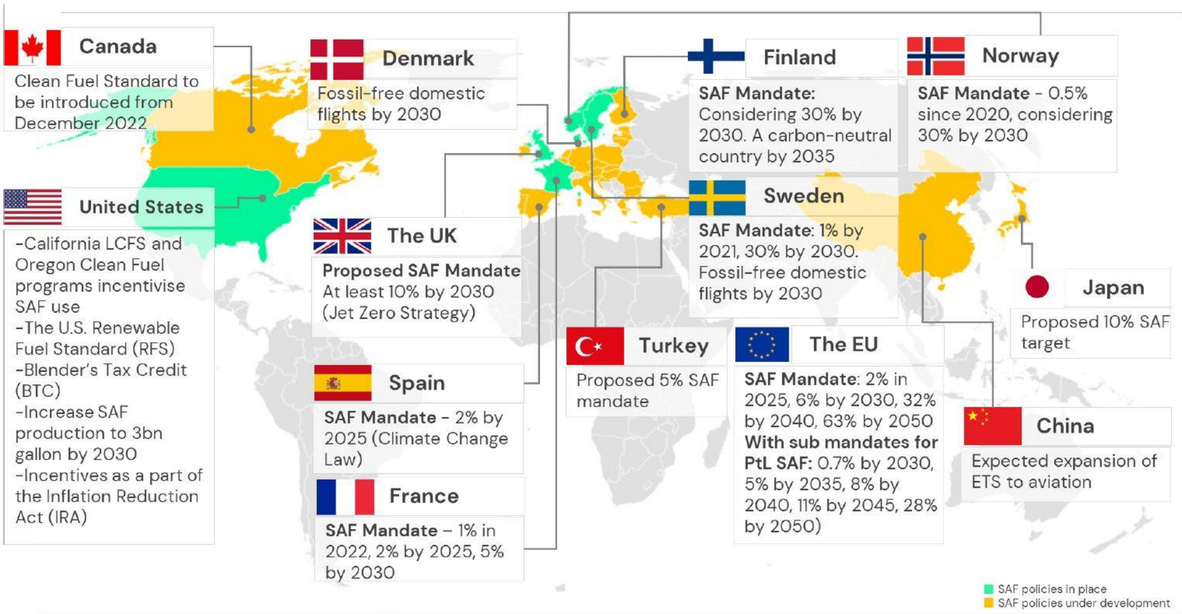

Figure 4 - Mandates and incentive policies in different countries (Airport World, 2022).

The European Commission has decided to use a mandate policy as first mechanism to speed up the development and deployment of SAF through the ReFuelEU Aviation regulatory proposal. In this context, the European Commission imposed the mixture of fossil-based aviation fuel with SAF for flights departing from European Union airports, with a percentage increase over time (from 2% 2025 to 70% in 2050) (ICAO, 2023). In Canada, the Aviation Climate Action Plan (2022-2030) has set the target of 10% for SAF use of by 2030 and aims to achieve the net-zero emissions by 2050 (Transport Canada, 2022). In India, the National Biofuels Coordination Committee has established a target of 1% blending of SAF with conventional jet fuel in 2027 for international flights initially and 2% blending in 2028 (S&P Global, 2023). Finally in Brazil, air operators will be required to reduce greenhouse gas emissions on domestic flights using SAF, starting in 2027 (Programa Nacional de Combustível Sustentável de Aviação – ProBioQAV). The targets start with a 1% reduction and gradually increase until reaching 10% in 2037 (S&P Global, 2022). In line with WP1, this report considers the regulatory and policy framework conditions that play a crucial role in defining systemic constraints and opportunities for SAF production.

1.2.4. SAF Producers and Production Capacities

The possibility of blending SAF with fossil-based jet fuel makes SAF a good solution for reducing CO_2 emissions. However, the production capacity and quantity of SAF are still limited. According to information from IATA, in 2023 SAF production reached more than 600 million litres, doubling the 300 million litres produced in the previous year. SAF was responsible for 3% of all renewable fuels produced. By 2024, SAF production is expected to triple to 1.875 billion litres (1.5 megatonnes), representing 0.53% of aviation fuel needs and 6% of renewable fuel capacity (IATA, 2023).

Table 5 shows some offtake agreements (in volume of SAF) established in 2023. In the last year, the biggest offtake agreements were established by Cemvita, USA Bioenergy and Raven SR, all from USA.

These 3 companies accounted for 73% of total offtake agreements, approximately. In Europe, Firefly located in United Kingdon, established the biggest offtake agreement, i.e. 655.9 million litres of SAF.

Table 5 - SAF offtake agreements in 2023 according to ICAO, 2024a

Supplier	SAF route	Fuel User/Purchaser	Total offtake volume (million litres)
DG Fuels		Air France - KLM	93.7
USA BioEnergy	FT	Southwest Airlines	3 255.5
Neste Oil	HEFA-SPK	Emirate, Viva Aerobus, Air Canada, Wiss Air, Boing	170.4
World Energy	ATJ, HEFA	DHL Express, World Fuel Services	770.2
OMV	Co-processed HEFA	Air France - KLM	2.5
Shell	FT	Emirates, Delta, JetBlue	95.2
Cemvita	HEFA	United Airlines	3 785.4
HCS Group		Lufthansa Group	75.0
Cleanjoule		Frontier Airlines, Wizz	340.7
Petronas		Malaysia Airlines	287.3
Dimensional Energy		Boom Supersonic	18.9
Repsol	HC-HEFA	Ryanair	196.8
Fulcrum	FT-SPK	Jet2.com	200.0
Firefly	HTL	Wizz Air	655.9
Gevo	ATJ	Hawaiian Airlines	189.3
IdunnH2		Icelandair	56.2
Raven SR	FT	Japan Airlines	1 561.6

Cemvita, the producer with largest offtake agreement in 2023, is based in Houston, USA. This leader in biological solutions for the energy industry produces sustainable oil from waste carbon sources. Cemvita works with partners in the sustainable oil refining stage, who produce SAF through the HEFA process (Businesswire, 2024). In September 2023, Cemvita Corporation announced a purchase agreement with United Airlines for up to 50 million gallons annually of SAF over 20 years obtained from CO_2 (Cemvita, 2023). In USA BioEnergy are converted woody biomass into renewable diesel, SAF and naphtha using gasification and FT technology. At a long-term strategy is focused on building of 12 advanced biorefineries. Each plant will produce 34 million gallons of renewable fuel by year and will can be extended to double that capacity (USA Bioenergy, 2024). Raven SR, headquartered in Wyoming, uses green waste, municipal solid waste, organic waste and biogas as feedstock in the production of renewable fuels such as diesel and SAF using the FT route. In January 2023, the company signed a memorandum committing to supply 50,000 tons of SAF to All Nippon Airways in 2025, with a gradual increase to 200,000 tons by 2035. (Raven, 2023) Firefly is a reference in sustainable fuels production. The process used by the UK company is HTL resulting in a crude oil that can be processed into SAF (Firefly, 2024). In April 2024, this company announced plans for the world's first SAF sewage plant in Harwich.

The Sustainable Aviation Fuel industry is experiencing significant growth, particularly in key regions around the world. The United States, Europe, and China possess the most developed SAF supply chains, with other Asian nations like Japan, India, New Zealand, and Singapore actively formulating their SAF strategies (KPMG, 2024), as can be seen by Figure 5.

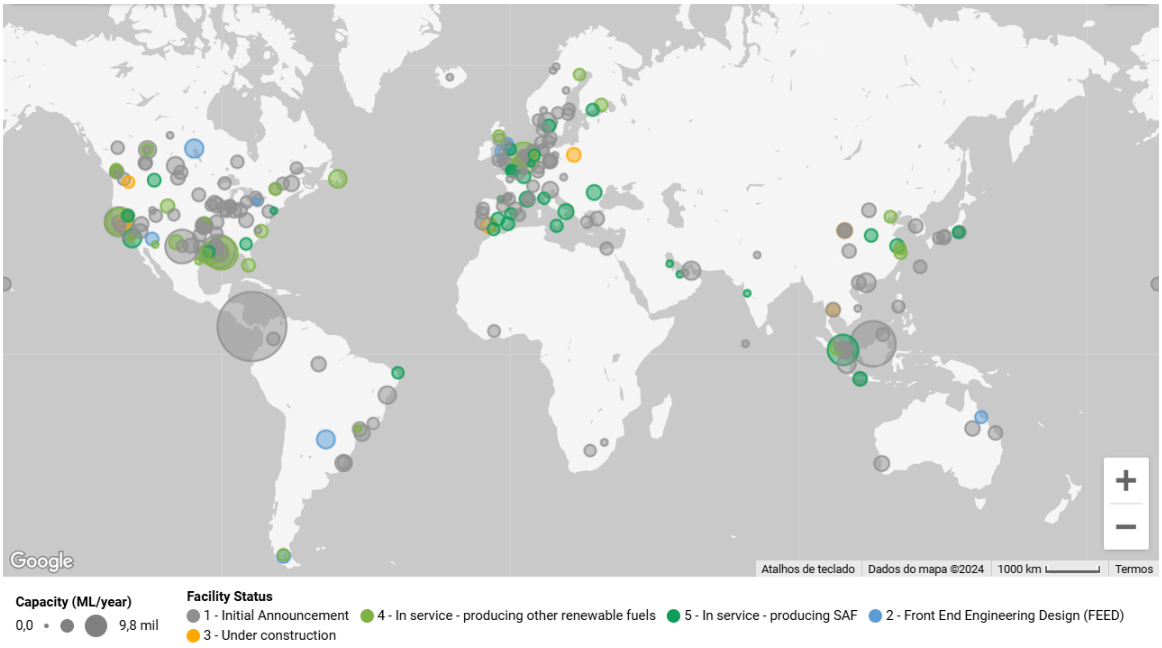

Figure 5 - Distribution of facilities existing and announced that could produce sustainable aviation fuels by countries according to ICAO, 2024b (capacity numbers refer to total capacity, including SAF and other renewable fuels).

At this moment, several plants of SAF production are in operation, under construction or announced as can be shown in Figure 5. According to ICAO, there are currently 33 SAF units in operation with announced capacity of 9.2 billion litres/year.

Table 6presents the production capacity of some companies that are currently in operation, according to information from ICAO. The company with the largest SAF production capacity is Neste located in Singapore. A world leader in the production of renewable fuels, Neste has a production potential of 3,375.0 million litres from renewable waste and residue materials, like tall oil, used cooking oil and animal fats through HEFA-SPK process.

Table 6 - Production capacity of current SAF producers according to ICAO, (2024b).

Supplier	Production Route	Capacity (million litres/year)
ADNOC	-	-
AirCompany	PtL	-
Atmosfair	PtL	0.5
BP	-	1.2
Calumet Specialty Partners	-	235.1
Cepsa	HEFA	98.4
ENI	-	762.0
EcoCeres	HEFA	375.0
Euglena/Chevron Lumus	HEFA-SPK	0.3
ExxonMobil	HEFA-Coprocessing	174.1
Fulcrum Bioenergy	FT-SPK	39.7
Gevo	ATJ	0.4
Junheng IndustryGroup Biotchnology Co Ltd	-	187.5
Lanzajet	ATJ	37.9
Neste Oil	HEFA-SPK	3 375.0
OMV Petrom	HEFA-Coprocessing	562.5
Pertamina	HEFA	348.0
Phillips 66	-	49.4
Praj	-	-
Repsol	HC-HEFA	250.0
Satorp	HEFA-Coprocessing	-
Senai	-	-

St1 Oy	HEFA	250.0
Total	HEFA/HEFA-SPK/ HEFA-Coprocessing	1 030.9
WorldEnergy	HEFA	1 158.3

The European region can be characterized as a key market for SAF, as there are many countries implementing regulations and policies to decrease aviation carbon footprint. It can be seen from the Figure 5 this region has the largest number of companies in operation (Reports and Insights, 2024). Passengers' choice for sustainable flights and the commitment of European airlines to reducing carbon emissions is further stimulating the increase in the use of SAF in Europe.

The SAF market in North America has seen a significant increase due to the great importance that has been given to environmental sustainability issues and the presence of large airlines. In this region also has many SAF production facilities. The USA, for example, has a high demand for SAF driven by regulatory initiatives and sustainability target. Additionally, consumer preference for environmentally friendly flights has increased, driving SAF consumption in that region (Reports and Insights, 2024).

The SAF market in the Asia-Pacific region has also seen a large increase due to the growth in air traffic and interest in sustainable development. In this region, Australia, Japan, and Singapore are the countries that have invested in SAF production and infrastructure development. The growing awareness of environmental issues among passengers and the support from the government are boosting the use of SAF in this region (Reports and Insights, 2024).

Currently, there is no commercial production of Sustainable Aviation Fuel (SAF) in Canada. However, several companies are actively developing SAF production technologies, including gasification, PtL, HTL, and co-processing. Plans for constructing HEFA facilities, which will produce both SAF and renewable diesel from fats, oils, and greases, have been announced. Nevertheless, SAF production in these facilities is not anticipated to begin before 2025 (GreenAir News, 2022).

In India, Praj's Sustainable Aviation Fuel demonstration facility was inaugurated on January 2024 (Praj, 2024). Praj uses the ATJ pathway to produce SAF from ethanol and isobutanol with a daily capacity of 25 kg. Commercial plant for SAF production is in conceptual stage, targeted to be operational by end 2026 with a capacity exceeding 200 ton/day.

There are two SAF industrial plants under construction owned by Brazilian group. One of these plants is in Paraguay (ECB Group) with estimated production capacity of 75,700 litres/day, divided between renewable diesel, SAF and green naphtha. The other plant (Brasil BioFuels) is situated in North Brazil and present an estimated production capacity of up to 280 million litres/year of SAF. The first plant is expected to start operating by 2024 and the second, by 2025 (S&P Global, 2022).

1.2.5. Required water resources in the SAF production pathways

In what concerns to resource efficiency utilization, namely water consumption, data are only found for HEFA and SIP technologies (Table7). For the HEFA pathway, by using oil source the water consumption values vary greatly from 5.5 to 13.90 m^3/GJ for pongamia and/or microalgae oil and up to 106.8 m^3/GJ with soybean oil. For the SIP pathway, water consumption is also high with great variability for sugarcane with a range from 15.60 m^3 to 147 m^3/GJ and 92-105 m3/GJ for switchgrass and 76-86m^3/GJ for corn grain. As can be seen, SIP pathway has higher water usage than HEFA route. These results build on the ongoing SAF yield improvements in WP2, where alternative feedstock schemes and mixed cropping systems are being tested to enhance biomass production while minimizing environmental footprints.

Table 7: Water usage considering the different SAF production pathways and feedstock. Values in m³/GJ adapted from Shahriar and Khanal, (2022). Kerosene type BP Jet A-1, 43.15 MJ/kg, density at 15 °C is 804 kg/m³ (34.69 MJ/liter) was considered for conversion.

Pathway	Source	Water consumption	
		m^3/GJ	L_{water}/L_{SAF}
HEFA	pongamia oil	11.8	409
	microalgae oil	13.9	482
	soybean oil	106.8	3705
SIP	sugarcane	147	5099
	switchgrass	104.7	3633
	corn grain	85.81	2977

1.2.6. Process yields and energy efficiency of the SAF production pathways

SAF production pathways with high yield and energy efficiency are desired for an economically viable process (Shahriar and Khanal, 2022). Table 8 summarizes the available data regarding energy efficiency and yield process for different routes of SAF production. Currently HEFA has the highest process yield with yields up to 0.7-ton SAF/ton feedstock. ATJ is the second route with the highest process yield (0.56-ton SAF/ton feedstock). The other routes have lower values that vary in the range of 0.13-0.36-ton SAF/ton feedstock. Regarding energy efficiency HEFA e ATJ have the highest values (0.91-0.92 GJOutput/GJInput) of energy produced with 1GJ of energy entering the process. While the FT and SIP pathways have the lowest energy efficiency values, 0.40-0.53 GJ_{Output}/GJ_{Input} and 0.50 GJOutput/GJInput, respectively.

Table 8 - SAF production pathways: process yield and energy efficiency adapted from De Jong et al., (2015).

Pathway	Process Yield[1] ton $_{SAF}$/ton $_{feedstock}$	Energy Efficiency[2] GJ_{OUTPUT}/GJ_{INPUT}
HEFA	0.75-0.83	0.92
FT	0.13-0.22	0.40-0.53
ATJ	0.56	0.91
SIP	0.17	0.50
HTL	0.18-0.36	0.64
Pyrolysis	0.16-0.36	0.63-0.77

[1] Total process yield is equal to ton of SAF per ton feedstock.
[2] Energy efficiency is equal to the ratio of the energy content of the final products and the energy input from feedstock and others.

1.2.7. Production costs and selling price of SAF

Production cost, the SAF availability and selling price are connected. The cost of SAF production is mainly determined by raw material and energy prices, conversion pathways, production scale, capital cost (Braun et al., 2024). According to the International Air Transport Association (IATA), in general, current price of raw materials can represent between 50-70% of the SAF production cost.

Figure 6 shows a projection for the production costs ranges of SAF, by the year 2025 for different production pathways of SAF. The production cost of SAF obtained through the HEFA route appears to be more competitive compared to others, which can be mainly attributed to its high production yield and low capital costs (Ng et al., 2021). However, SAF produced through this production pathway is not cost competitive to petroleum-based jet fuel yet. In this Figure, SAF produced by the ATJ route has the highest production costs compared to other routes, which is probably due to the use of second-generation alcohol as raw material.

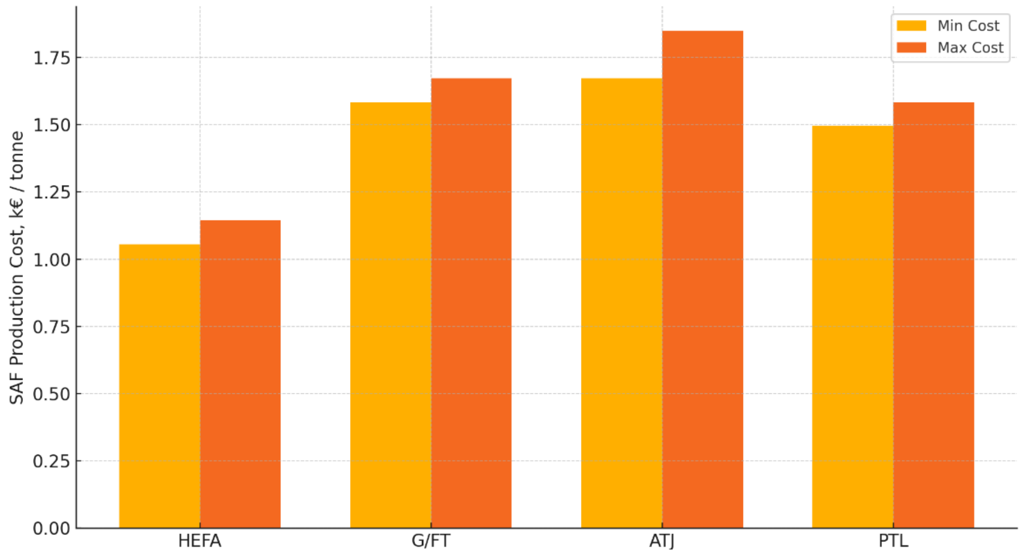

Figure 6 - SAF production cost ranges by synthesis pathway adapted from Wolf, (2021).

SAF is currently more expensive than conventional jet fuel, which presents a challenge to its broader adoption. SAF prices are 1.5 to 6 times higher than conventional jet fuel (EASA, 2022). Although according to IATA, the wholesale price of SAF in 2023 was 2200 EUR/ton, 2.8 times more expensive than conventional jet fuel (IATA, 2024).

It is important to emphasize that the selling price of SAFs is not only influenced by the cost of production, but also by availability and demand. So, sales and market prices of SAF may differ significantly. In the current scenario, the requirements for blends of SAF with petroleum-based aviation fuel are likely to keep the price of biofuel high, as the aviation industry must comply with the mandatory incorporation quotas and the SAF supply is still limited (Braun, et al., 2024). However, it is not possible to accurately predict changes in SAF prices in the following years. A decreasing trend in SAF production costs is expected in the long term due to technological advances, economic incentives and potential tax credits (EASA, 2022). It has been reported that the wholesale price of SAF in 2021 was on average 3.6 times more expensive than conventional jet fuel, which shows a decrease compared to the value reported for 2023, reinforcing the trend described previously. The economic analysis aligns with ongoing work in WP3, which is focused on assessing the cost-effectiveness of various SAF production technologies, including capital and operational expenditures."

1.2.8. CO_2 emission reduction

SAF's sustainability is underpinned by critical benchmarks, including notably reduced lifecycle greenhouse gas (GHG) emissions when contrasted with fossil fuels, alongside minimal biodiversity impact and no competition with essential resources like food and water (Yoo, et al., 2022; IATA, 2024a). Lifecycle GHG emission reductions can vary depending on the feedstock and technology used, as shown in Figure 7.

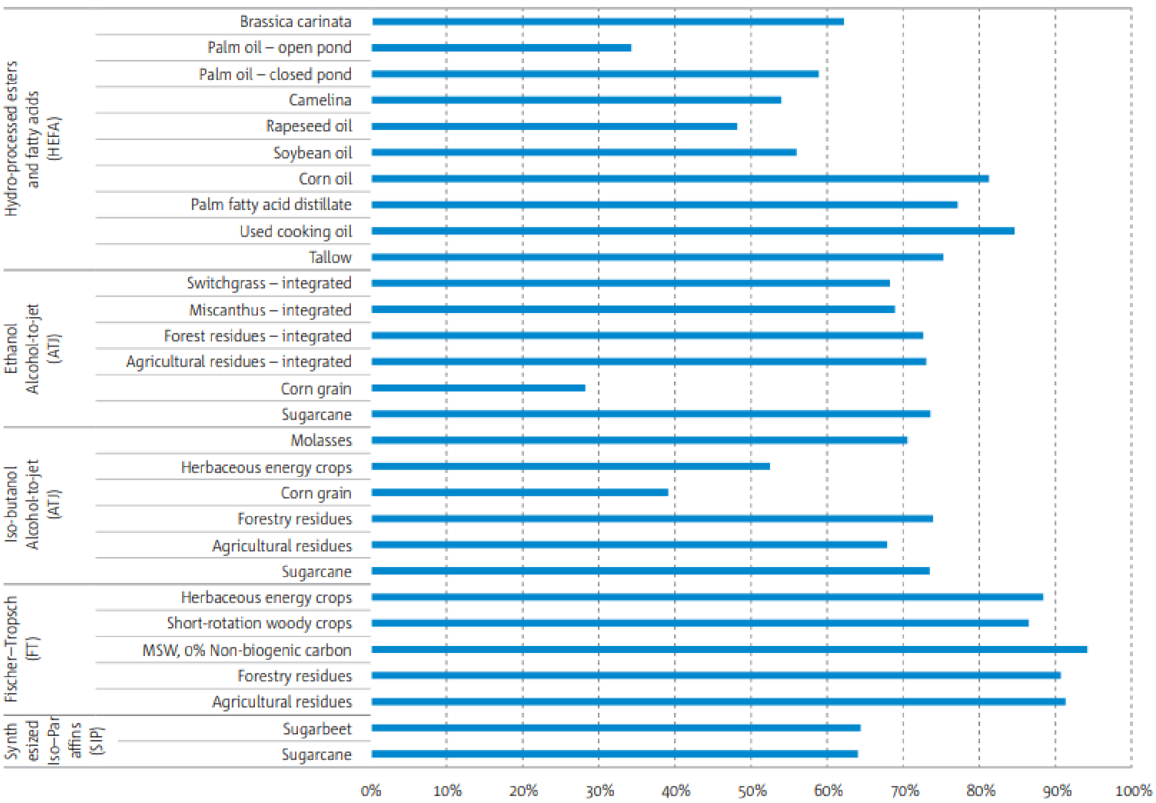

Figure 7 - Reduction in CO_2 emissions for different routes and raw materials used in the production of SAF compared to conventional aviation fuel (reference value 89 g CO2eq/MJ) according to EASA, (2022)

By comparing conventional jet fuel, neat SAF has the potential to reduce greenhouse gas emissions by an estimated range of approximately 30% for ATJ using corn grain to 95% for FT using MSW. Note that in general the FT route is the most efficient in reducing greenhouse gases with compared to other pathways. The HEFA route, using corn oil and used cooking oil also presents high values of reduction in CO_2 (more than 80%). On the other hand, the lowest values for emissions were observed or by the same route, with a value of less than 30% to corn grain. In general, most of the raw materials being used by the routes presented have the potential to reduce greenhouse gas emissions by at least 70%. Considering that the carbon footprint of sustainable aviation fuels (SAFs) can vary significantly based on factors such as feedstock type, transport distances, conversion methods, biofuel plant process designs, industrial scale, and regional conditions, it is essential to conduct specific life cycle assessment (LCA) case studies. In ICARUS Work Package 3, specific case studies will more precisely determine greenhouse gas (GHG) emissions and identify technology bottlenecks that impact the environmental footprints of SAFs.

1.2.9. Acceptance by airlines and passengers

The journey towards adopting SAF has seen remarkable milestones, with airlines across the globe taking significant strides to integrate SAF into their operation, driven by the urgent need for decarbonization and sustainable aviation practices. The industry's commitment to SAF is evident in the groundbreaking initiatives and collaborations aimed at reducing carbon emissions and achieving net-zero targets by 2050. Virgin Atlantic has been at the forefront of this transition, making a historic achievement with flight VS100, the world's first transatlantic flight using 100% SAF, from London Heathrow to New York JFK. This flight utilized a blend of 88% hydroprocessed esters and fatty acids (HEFA) supplied by Air BP and 12% synthetic aromatic kerosene (SAK supplied by Virent, showcasing the potential of SAF to significantly reduce aviation's carbon footprint.

Similarly, Emirates Airlines demonstrated the viability of SAF by completing a demonstration flight with an Airbus A380, where one of the four engines was powered entirely by SAF. This initiative, in collaboration with Airbus, emphasizes the feasibility of using drop-in sustainable fuels as alternatives to conventional jet fuel, further proving the industry's capability to embrace cleaner energy sources.

The commitment to SAF is not limited to these airlines; over 50 airlines worldwide have now experimented with SAF, reflecting a collective effort to transition towards more sustainable fuelling solutions. Despite SAF currently accounting for approximately 0.1% of all jetfuel used globally, the industry is witnessing a gradual increase in its production and use, with over 300 million litres produced in 2022 and over 600 million litres in 2023.

Significant commitments have been made by the airlines to increase the use of SAF. At the World Economic Forum's Clean Skies for tomorrow coalition event in September 2021., 60 companies, including major airlines like British airways, Delta Airlines, KLM, United Airlines, and Virgin Glactic, pledged to work together towards powering global aviation with 10% SAF by 2030.

Furthering these efforts, airlines within the Oneworld Airlines Alliance, such as Alaska Airline, America Airlines, British Airways, Finnair, Japan Airlines, and Qatar Airways, announced plans in July 2022 to purchase up to 200 million gallons of ethanol-based SAF per year from renewable fuels producer Gevo. This commitment is set to commence in 2027 for operations at several major Californian airports.

Ryanair has also taken significant steps by announcing plans to operate about a third of all flights from Amsterdam's Schipol Airport with a 40% SAF blend. Cathay Pacific launched its Corporate Sustainable Aviation Fuel program, enabling commercial customers to contribute towards using SAF on passenger and cargo flights from Hong Kong International Airport. Moreover, DHL Express has committed to purchasing over 800 million litres of SAF for the next five years through partnerships with BP and SAF producer Neste.

In fact, there is a clear sign from many airlines to guarantee SAF usage. According to ICAO (International Civil Aviation Organization), the aviation industry is currently working with SAF productors under Offtake agreements. During 2022, 43 agreements were announced, corresponding to 21,7 ML of SAF, while during 2023, 26 agreements were announced, totalling 1,4 ML annual SAF production. Since 2013, 123 offtake agreements were announced, which sums up to 52.5 ML ICAO. (2024a). There is also an effort on the airports to offer SAF to fuel airplanes. From 2024, is expected that a total of 125 airports receive deliveries, 81 of them ongoing and 44 by batch deliveries. (ICAO, 2024d).

These initiatives are complemented by investments in various manufacturing methods for SAF. Companied like JetBlue, Virgin Atlantic, the US Air Force, and Boom Supersonic are investing in innovative technologies such as those developed by Air Company, which claims to have created the first carbon-neutral jet fuel derived from captured carbon dioxide.

According to information from ICAO, currently 109 airports around the globe distribute SAF, 69 of which have a continuous supply system and the rest have an on-demand supply system. Of these airports, more than two thirds are located in the US and Europe. In addition to these, SAF is also distributed at 2 airports in Japan (Haneda and Narita) and China (Ningbo and Tianjin) (Bluebiz, 2024). Figure 8 shows the distribution of airports worldwide supplying SAF for air transport operations.

The aircraft's engines are certified to use blends up to 50%, but 100% SAF usage is being tested (ICAO, 2024).

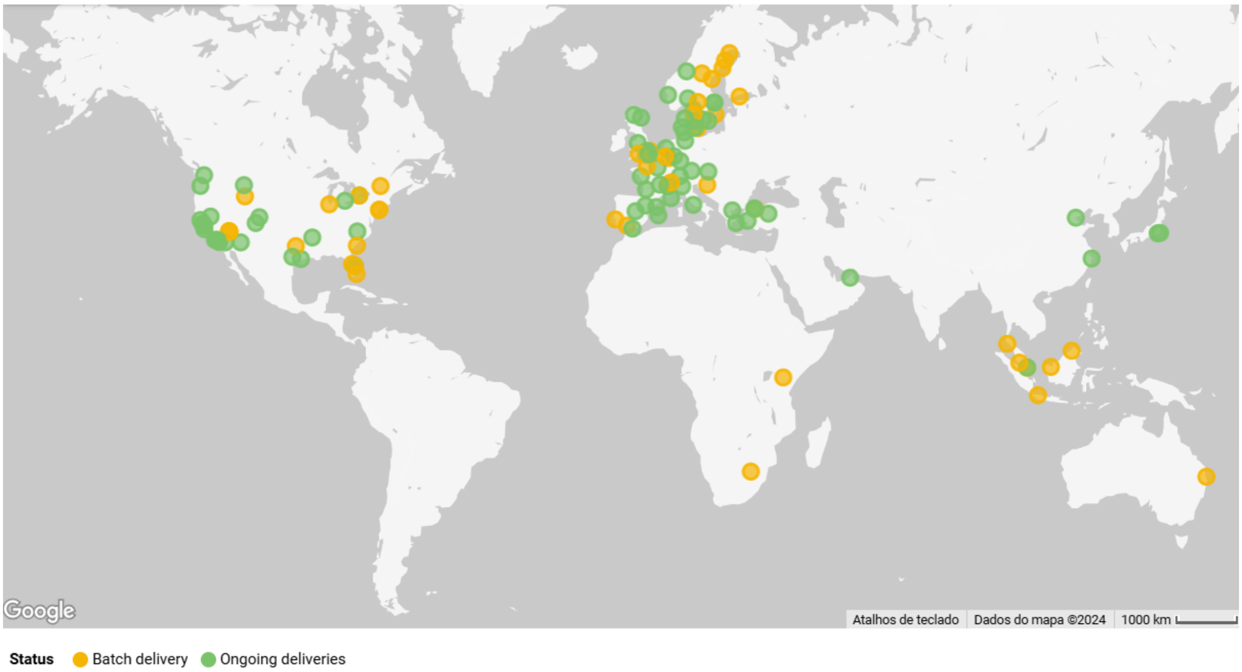

Figure 8 - Airports worldwide supplying SAF according to ICAO, 2024d.

As the aviation industry continues to evolve in response to environmental demands and changing consumer preferences, these concerted efforts by airlines to adopt and invest in SAF underscore the sectors' commitment to sustainability and its role in combating climate change. In line with WP3 social analysis that covers public perception and acceptance of SAF, this report considers the social acceptance of SAF, taking into account public perceptions and socio-economic factors that may affect its adoption.

1.3. SWOT analysis

The sustainable aviation fuel supply chain is essential for the aviation industry's shift towards sustainability. However, it faces several challenges and limitations. SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) of the supply chain of SAF was carried out to identify key points and establish action priorities, emphasizing failures, problems and possible solutions of these routes and the results are present in Table 9. This Table identifies the internal factors (strengths and weaknesses) that are inherent to the current state of the SAF supply chain, as well as the external factors (opportunities and threats) that could influence its future development.

Table 9: SWOT analysis of SAF supply chain.

Internal	
Strengths	**Weaknesses**

• Reduced greenhouse gas emissions compared to conventional jet fuels. • Technological advancements improve SAF production efficiency. • SAF can be used without need for further modification to the aircraft engines or infrastructures. • SAF is obtained from sustainable feedstocks. • Governments worldwide are actively supporting the development and deployment of SAF through financial incentives and policies. • SAF can improve air quality by reducing PM and sulfur emissions. • SAF production can improve rural economies. • Alternative source of fuel. HTL • Drying of raw materials is not necessary for use via the HTL route. • It may be possible to co-process the bio-oil obtained in traditional refineries, since the upgrading uses standard refining processes. • The bio-crude obtained is energy-dense. FT • In the gasification process can be used low-cost feedstocks (residues and wastes) • This route produces high-quality sustainable aviation fuel ATJ • Like HEFA, ATJ can be co-processed in traditional refineries directly to SAF by well-known petrochemical processes.	• Limited feedstock availability restricts production capacity. • High production costs compared to conventional jet fuel. • Supply chain infrastructure for SAF is still under development. • Policy frameworks in support of SAF are not yet globally standardized. • Competition for resources and incentives with other sectors. • High costs of financing of SAF fuel production infrastructure. • Global SAF production capacity is still limited at present. • SAF is consumed in very small volumes compared to conventional jet fuel due to the currently authorized blending amount. HTL • HTL occurs at high temperatures and pressures. • The HTL pathway is not well developed yet. • Bio-crude with high water and oxygen content can modify catalysts and the products obtained (quality?). • The bio-crude produced is corrosive and can create problems in downstream processing. • High costs of processing or recycling wastewater containing significant amounts of organic material. • This route is not certified yet. FT • The syngas used in the FT process has high purity quality requirements • This route may require high energy demand. • High initial investment for plants using the FT process. ATJ • 2G ethanol production needs to reduce production costs. • Continuous high pressure lignocellulosic biomass pretreatment is still an issue due to biomass impurities from the field. • ATJ pathway presents high capital costs.
External	

Opportunities	Threats
Common for all: HEFA, FT and ATJ • Growing public and governmental support for sustainable fuels through policies and incentives. • Opening new markets for SAF to reduce aviation's carbon footprint. • Potential for technological innovation to leading to lower production costs. • SAF stands to benefit from a growing demand in the aviation industry, driven by airlines and governments seeking to reduce carbon footprints. • Expansion of the range of sustainable raw materials for SAF production. • The construction of more fuel-efficient aircraft and the increased demand for sustainable flights can boost the use of SAF. • SAF could reduce dependence on petroleum-based jet fuel imports.	Common for all: HEFA, FT and ATJ • Competitive demand for feedstocks required by other renewable energy industries. • Fluctuating oil prices impact the cost competitiveness of SAF. • Need for a robust accounting framework to support global SAF adoption. • Economic crises could reduce demand for SAF, making it difficult to increase production. • The development of electric aircraft or hydrogen fuel cells could limit SAF production. • A decrease in government support or significant security incidents involving SAF could impede the increase in its production.

The strengths of SAF lie primarily in its potential to significantly reduce the aviation industry's carbon emissions and the increasing efficiency of production technologies. However, the supply chain is weakened by factors such as high production costs and incomplete infrastructure for widespread distribution. These costs are particularly notable when compared to conventional fuels, which benefit from well-established supply chains and economies of scale (WBCSD, 2020 and Martinez-Valencia, 2021).

Opportunities for the SAF supply chain are abundant and include potential market growth driven by increasing environmental consciousness, policy support, and technological advances that could reduce costs. Research and development can unlock more efficient production methods, increase the variety of feedstocks, and integrate the supply chain more effectively with existing agriculture and waste management systems (Assa, 2019; Martinez-Valencia, 2021; Ernst & Young 2023).

Conversely, the supply chain faces threats such as competition for feedstocks from other bioenergy sectors, possible disruption due to volatile oil markets, and the challenge of establishing an international framework for monitoring and accrediting SAF usage to ensure accountability and support consumer confidence (TOPSOE, 2022; IATA, 2023a; Singh, 2023).

One of the foremost bottlenecks currently limiting the SAF supply chain comes from feedstock availability. Production relies heavily on the specific type of biomass, which can be in limited supply or face unsustainable harvesting pressures. Additionally, the disparity in policy frameworks across different regions can slow down international coordination and market adoption of SAF, (Shahriar and Khanal, 2022; Mungiu and Brown, 2022; S&P Global 2022a; TOPSOE, 2022), while allowing carbon leakage from more restrict to more permissive regions.

Moreover, while there is potential to expand the SAF market, its development could be hampered by cost issues. Given that the production of SAF is currently more expensive than traditional jet fuel, without policy interventions or significant technological breakthroughs, the widespread implementation of SAF may be slowed.

The SAF supply chain is a critical element in the aviation industry's path towards a sustainable future. While there are significant hurdles to overcome, particularly in the cost and infrastructure domains, there are also substantial opportunities for growth and innovation. Stakeholders across the supply chain must work together to leverage strengths, address weaknesses, examine opportunities, and prepare for threats to create a robust SAF market.

2. Future State and Goals

2.1. Projected SAF Supply Chain Status

2.1.1. Estimate production of SAF and future Capacities

According to IATA, the World to achieve net-zero goals in aviation, 23 billion litres of SAF would be required by 2030. Looking towards, this demand is expected to rise to approximately 230 billion litres by 2040 and 450 billion litres by 2050, as shown in Figure 9. These values illustrate the huge challenge necessary in SAF production, to support the aviation industry's decarbonization efforts.

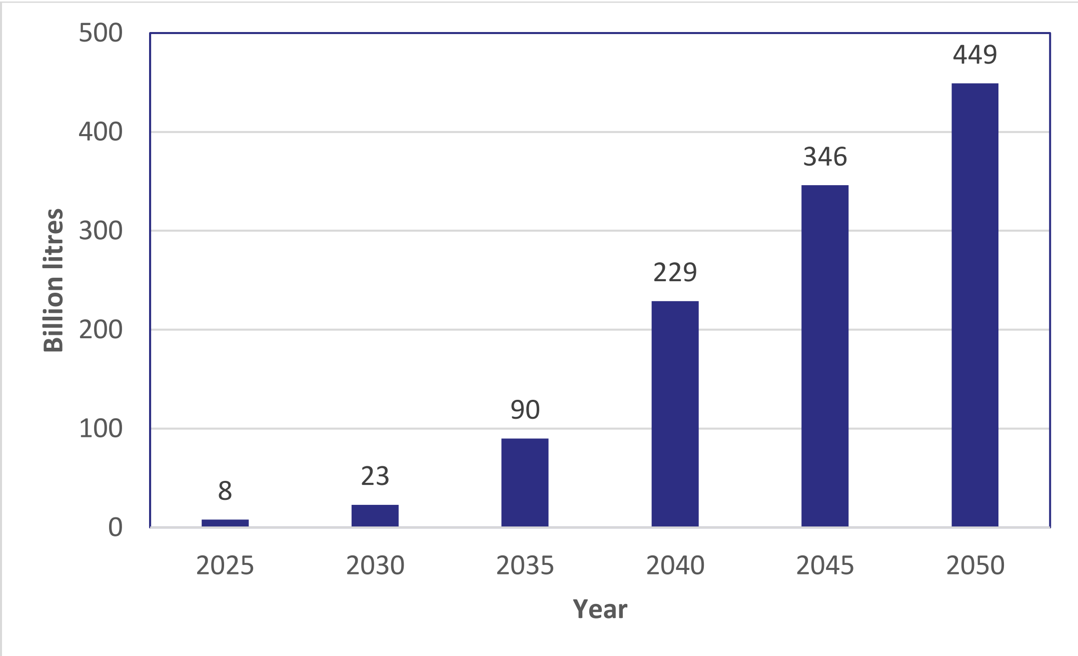

Figure 9 - Expected SAF production to reach a Net-Zero goals according to IATA (2024a).

In the next years, the desired state of the SAF supply chain envisions a significant increase in SAF production capacity to meet intermediate sustainability targets, if compared to actual capacity. However, as shown by Figure below, the capacity is lower than that required to make significant progress towards the Net-Zero target by 2050. SAF production capacity around 13.5 billion litres per year may be available by 2032. This value may be even lower due to uncertainty. The figure shows high ratio and low ratio, highlighting this uncertainty.

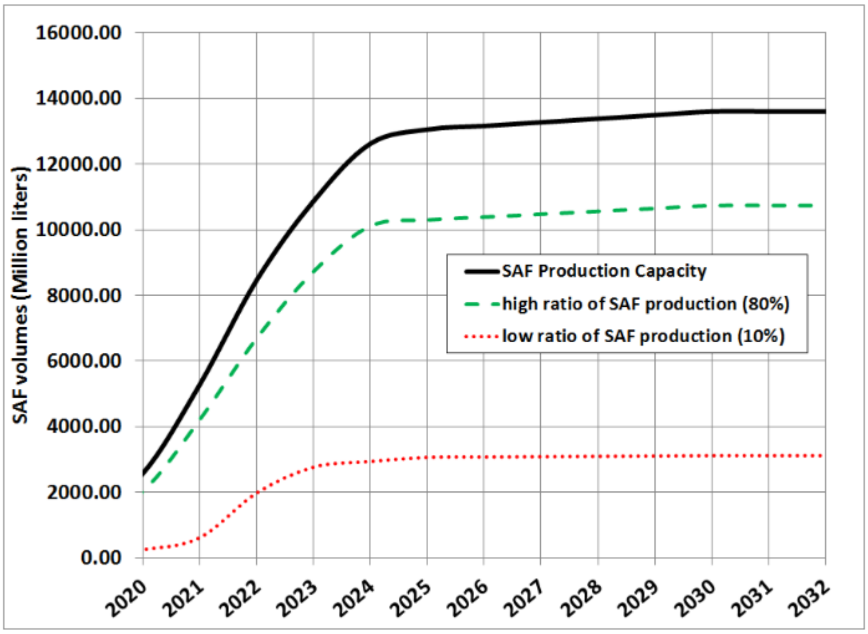

Figure 10 - Projected scenarios of SAF production capacity according to ICAO, (2024f).

It was possible to divide the global demand for SAF by world regions, considering the projected number of flights, as shown in the Figure 11. Here it is clear that the SAF market in the Asia-Pacific (APAC) will be fast growing. This is due to the fact due to an expected increase in low-cost airlines and rapid advancement of infrastructure, which justifies the higher SAF value in this region. Europe (EU and Non-EU Europe) will be the second region with the highest demand for SAF by 2050, followed by North America and Latin America and the Caribbean. And finally, the region with the lowest demand will be Africa, with much lower values compared to the other regions.

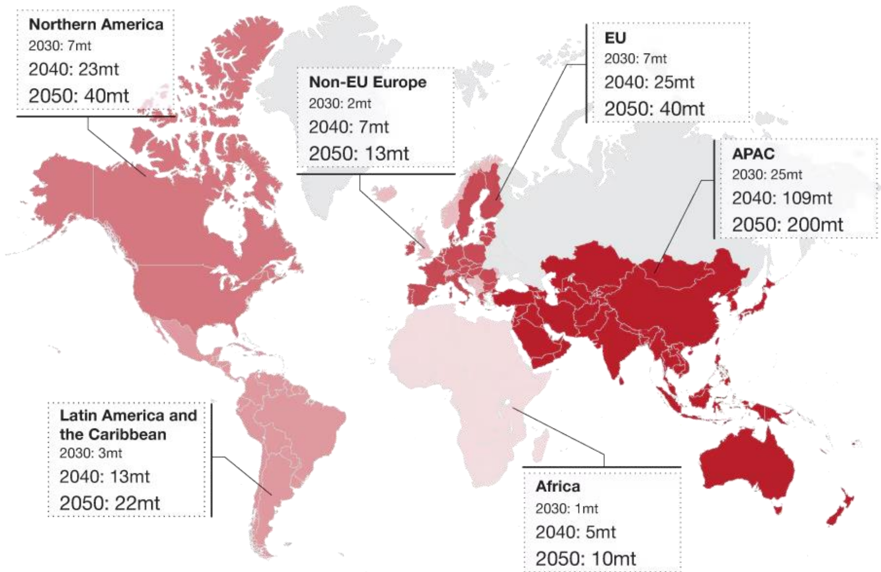

Figure 11 - Global SAF demand (in Million metric tons) across the regions, according to Strategy&, (2023).

Looking ahead to 2050, the SAF supply chain should be fully matured, with SAF providing a major portion of the aviation fuel market, contributing to around 65% of the reduction in aviation emissions necessary for achieving net-zero CO_2 emissions. This will require continuous technology developments, significant infrastructural investments, and robust market mechanisms to ensure that SAF is both affordable and widely available. By 2050, it is anticipated that SAF production will be fully integrated into the global fuel supply chain, supported by a diverse range of feedstocks and advanced production technologies.

As mentioned before, there are currently 33 SAF units in operation. However, according to the ICAO, the production of renewable fuels could increase significantly in coming years due to 6 facilities under construction and a further 225 facilities in initial announcement that together could reach production of 75 billion litres/year including SAF as shown in Figure 12. Below is presented a Figure showing the number of facilities that are under construction or initial announcement in the coming years, by country.

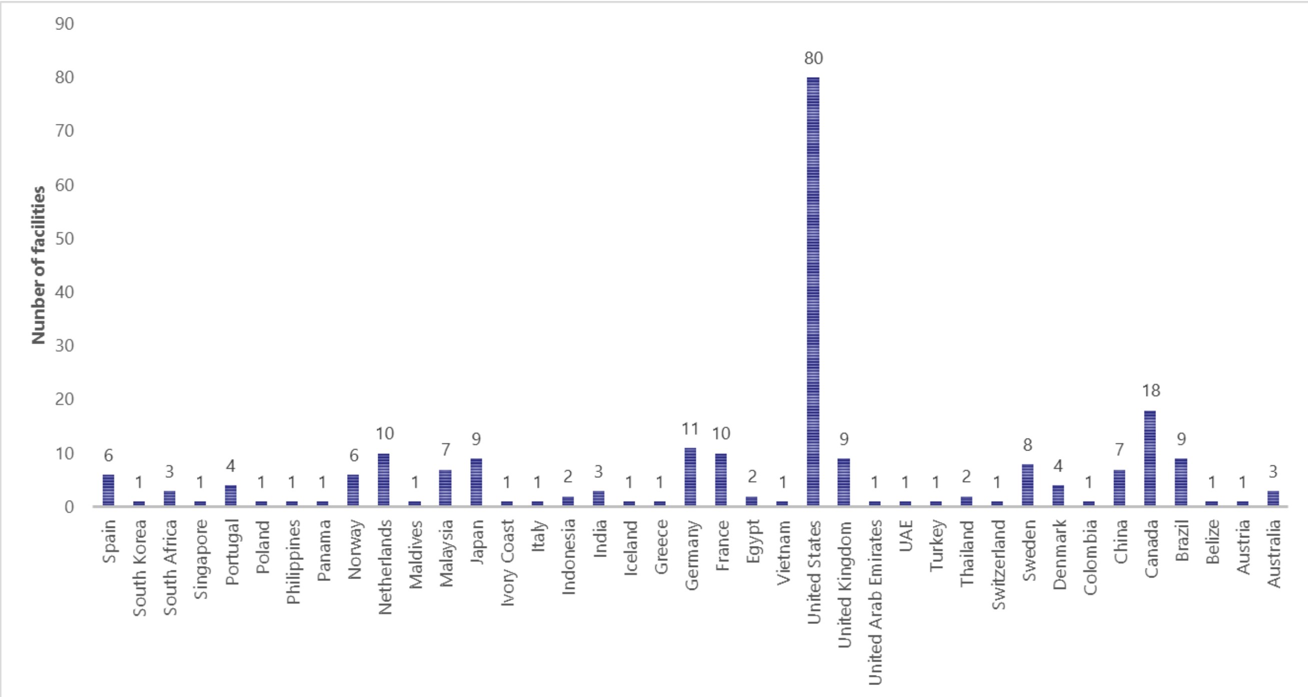

Figure 12 - Facilities of SAF under construction or initial announcement, by country (ICAO, 2024b).

2.1.2. Development of current pathways of SAF production, emergent technologies and certifications

The ambitious objective of achieving Net-Zero targets highlights the industry's commitment to enhancing SAF production and the utilization of sustainable biomass and CO_2 capture. According to the data presented in Table 10, substantial advancements in SAF production pathways like HEFA and ATJ will be seen by 2030, with significant scaling expected by 2040 and 2050 through ATJ, PtL, and Gasification + FT (G+FT) routes. It is believed that in 2040 and 2050 ATJ, PtL and G+FT will be the most used routes.

Table 10 - SAF supply in the EU27 through different routes in the next years in million tonnes according to EASA, (2022).

	2030	2040	2050
Electricity	0.00	0.00	0.20
Gasification + FT	0.00	4.50	5.90
PtL	0.30	3.70	12.70
ATJ	0.80	3.50	5.80
HEFA	0.80	1.30	1.80
Imports	0.40	1.80	2.30

By 2030, it is essential that SAF production pathways and feedstocks adhere to recognized certifications to ensure sustainability and market acceptance. The primary standard for SAF is ASTM D4054, which includes rigorous testing to guarantee safety and performance. Achieving certification under this standard will facilitate the commercial use of SAF in aviation. According to the data presented in Table 10, all forecasts for 2040 and 2050 indicate that the HEFA technology, currently predominant for SAF, will lose importance to FT and ATJ technologies, primarily due to limitations in obtaining sustainable oils.

Innovation and research are critical to the advancement of SAF production technologies. In the years to come, emerging technologies not only PtL, but also HTL, Aqueous phase reforming, Lignin to jet, photofermentation should be moving towards commercialization, supported by ongoing research and pilot projects. These technologies offer the potential for higher efficiency and lower environmental impact compared to other technologies. Figure 13 shows the flowchart of emerging technologies of SAF production from biomass (Lau et a., 2024).

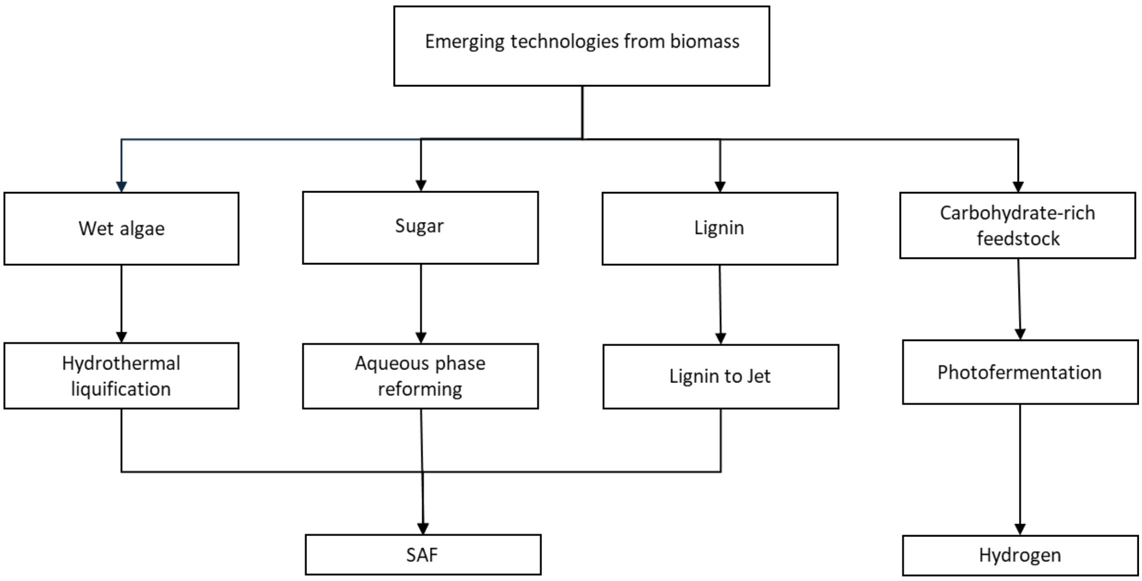

Figure 13 - Emerging technologies for SAF production.

By 2050, the vision is that some or even all these emerging technologies to be fully commercialized and integrated into the SAF supply chain. Continuous innovation will be necessary to further enhance production efficiencies and sustainability, ensuring that SAF remains a viable and competitive alternative to fossil jet fuel. Additional feedstocks should be identified to leverage all SAF technologies by promoting diversification and regional options (IATA, 2023). Through collaboration, innovation, and investment in sustainable technologies and fuels, the aviation industry is paving the way to a more sustainable future.

As stated before, to date, eleven technologies for generating aviation fuel from biomass have been certified, with more than eleven additional technologies currently in the certification process, expected to be achieved by 2030. These include advanced processes for processing lignocellulosic biomass using methods such as pyrolysis, hydrothermal liquefaction, and subsequent hydrotreatment. While no components in these areas have been certified yet, significant progress is being made, with companies, like Shell, by developing advanced technologies, such as IH2 hydropyrolysis, towards industrial implementation (Ershov et al., 2023).

By 2030, it is expected that many more SAF production pathways will be certified, facilitating broader adoption and integration into the aviation fuel supply chain. The continuous development and certification of new SAF technologies are crucial. Recognized certifications, such as those from the Roundtable on Sustainable Biomaterials (RSB) and the International Sustainability and Carbon Certification (ISCC), will provide assurance that SAF adheres to strict sustainability criteria.

By 2050, the goal is for all SAF used in aviation to be certified to the highest sustainability standards, ensuring minimal environmental impact and maximum efficiency. Continuous improvements in certification processes will help streamline the integration of new SAF technologies and feedstocks, fostering innovation and growth in the sector. Achieving Net-Zero emissions by 2050 is a realistic goal for the aviation sector through a combination of SAF utilization, CCS (Carbon Capture and Storage), and BEECS (Bioenergy with Carbon Capture and Storage) technologies, which will help offset any remaining emissions.

2.1.3. Estimation of sustainable feedstock production and innovation in feedstocks

According to a recent report from the European Commission (2023), the development and scaling of advanced biofuel technologies are crucial for meeting future SAF demands. The report emphasizes the importance of expanding feedstock availability and improving supply chain efficiencies to support large-scale SAF production. By 2030, sustainable feedstock production must ramp up to support the growing demand for SAF. To achieve the desired state by 2030, sustainable feedstock production will focus on leveraging existing waste streams and improving agricultural yields through precision farming and other advanced techniques. For instance, utilizing cover crops and agricultural residues like straw and corn stover can provide a significant source of biomass without competing with food crops. Advancements in agricultural practices and waste management systems are expected to enhance the availability and sustainability of these feedstocks. Maximizing the use of waste oils, fats, greases, agricultural residues, and non-food crops can also help to achieve the desired yields.

By 2050, the vision for sustainable feedstock production includes a fully developed and efficient supply chain capable of meeting the large-scale demand for SAF. This will involve extensive use of diverse feedstocks, including algae and other innovative biomass sources. The goal is to ensure that all feedstocks used for SAF production are sustainable, with minimal environmental impact and no competition with food production.

2.1.4. Required energy and water resources

Producing SAF, especially through PtL technologies, requires significant energy and water resources. The production of 1 kg of PtL fuel is estimated to demand around 42 kWh of electricity. This value accounts for various CO_2 sources, including both pure and scrubbed CO_2 from point sources, with an additional 20% coming from direct air capture (DAC) (Drünert et al., 2020).

DAC demands more energy than capturing CO_2 from specific sources, resulting in increased fuel costs. However, the confidence intervals for these costs overlap (Seymour et al., 2024). Consequently, the electricity required for producing a substantial amount of PtL fuel is considerable.

For example, to meet Germany's aviation fuel needs in 2019, which totalled 10.3 million tonnes, approximately 440 TWh of electricity would be necessary, if all SAF could be produced from PtL pathway. This would represent approximately 86% of Germany's total electricity consumption in 2019, which was around 512 TWh (Eurostat, 2024). Predictions indicate that by 2030, Germany's electricity consumption is expected to increase to around 600 TWh, further underscoring the immense energy requirements for large-scale SAF production (Eurostat, 2024a). Meeting such high electricity demands will require substantial investments in renewable energy infrastructure, as PtL fuel production needs to be powered by sustainable energy sources to maximize environmental benefits. And due to the additionality principle of RED III, it will not be easy for any EU Member State, due to the opposition of environmentalists NGOs, to expand significantly the land use for increasing the capacity for solar, and other renewable energy sources crucial to provide the necessary renewable electricity while minimizing carbon emissions associated with SAF production.

For HEFA, ATJ, and FT pathways, literature provides data on energy requirements. FT processes, for example, indicate that producing 1 kg of syngas requires approximately 12-15 kWh of electricity when using electric gasifiers (Naqvi et al., 2020). Afterward, the conversion of syngas to SAF adds additional energy demands, typically around 20-25 kWh per kg of SAF (Seymour et al., 2024). In ATJ pathways, refinery processes such as hydrodeoxygenation and hydrogenation primarily rely on heat but still require substantial electricity, particularly during initial conversion and purification steps. The energy efficiency of the ATJ process is approximately 0.91 GJ_{output}/GJ_{input} (0.8255 kWh per kilogram of SAF). Furthermore, a recent study by the International Energy Agency (IEA) estimates that the production of SAF through HEFA pathways requires approximately 0.8255 kWh per kilogram of SAF, with most of the energy coming from hydrogen production and the hydroprocessing stages (IEA, 2024). The energy efficiency of different SAF production pathways varies significantly, FT processes showing an efficiency of approximately 43.6%, HEFA reaching up to 74%, and ATJ around 39.3% (Grim et al., 2022). These efficiencies highlight that while HEFA is currently the most energy-efficient pathway, FT and ATJ processes also contribute significantly to SAF production with ongoing improvements needed to enhance their efficiencies further. Electrifying SAF production pathways, particularly through the integration of renewable energy sources, offers several economic and environmental benefits, including a reduction in greenhouse gas emissions, cost reduction through technological advancements, increased energy security and stability, and economic opportunities through investment in renewable energy infrastructure and SAF production facilities. (Department of Energy, U.S., 2020; Seymour et al., 2024).

In addition to energy requirements, water usage is another critical factor in SAF production. The production processes for SAF, particularly those involving biomass conversion and PtL technologies, require significant water inputs. Efficient water management practices and innovations in water recycling and reduction technologies will be essential to minimize the environmental impact and ensure the sustainability of SAF production.

By 2030, the goal is to have robust systems in place for managing the energy and water demands of SAF production. This includes integrating renewable energy sources to meet the high electricity requirements and implementing advanced water management practices to optimize resource use. Looking ahead to 2050, the vision is for SAF production to be fully sustainable, with minimal environmental impact and resource usage optimized through technological advancements and efficient practices.

2.1.5. Greenhouse gas emissions reduction forecast

By 2030, the adoption of SAF is expected to start to make a significant impact on reducing greenhouse gas emissions in the aviation sector. Projections for 2030 indicate that blending mandates and increased SAF production could lead to a reduction in CO_2 emissions by 5% in the air transport sector. This means that from the 682 megatonnes of CO_2 expected to be globally produced by international flights in 2030, 34 megatonnes can be reduced through SAF usage. The implementation of comparative lifecycle analysis (LCA) methodologies for aviation sector, will ensure that these reductions are accurately measured and reported.

Looking towards 2050, the global forecast is for SAF, including all advanced biofuels and PtL technology, to contribute approximately 65% of the emission reductions needed by the aviation sector to reach net zero CO_2 emissions, according to Figure 14. This ambitious target will require not only increased production but also advancements in the efficiency and sustainability of SAF production processes. By achieving these goals, SAF will play a crucial role in mitigating the environmental impact of aviation.

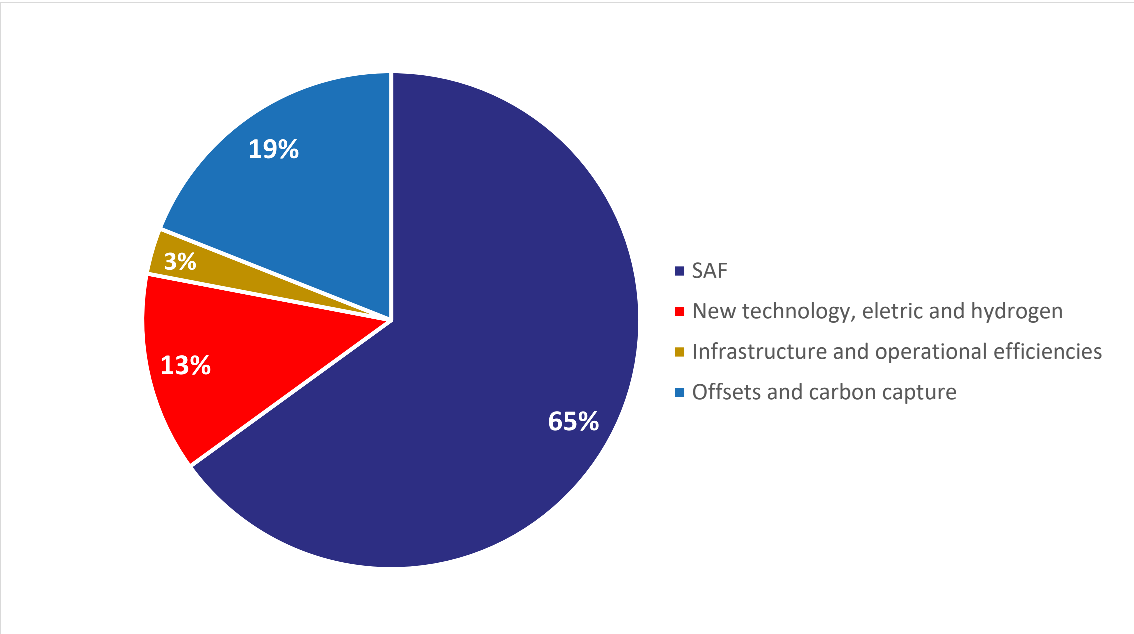

Figure 14 – Global projected contribution of SAF to meet the Net ZERO 2050 according to IATA, 2024a.

Figure 15 shows the impact of using SAF could have on the global emissions of the European aviation sector. The graph presents a detailed analysis of the projected carbon dioxide equivalent (CO_{2eq}) emissions from aviation and the potential impact of Sustainable Aviation Fuel (SAF) from 2030 to 2050. According to the data, CO_{2eq} emissions are anticipated to rise gradually, from 183 million tons in 2030 to 189 million tons in 2050. This upward trend suggests that the overall demand for air travel and associated emissions will continue to grow, even as more sustainable practices are implemented. Despite this increase in absolute emissions, the introduction and scaling up of SAF play a crucial role in mitigating the environmental impact of aviation. The percentage reduction in CO_{2eq} emissions due to SAF usage is projected to increase significantly over the next three decades. In 2030, SAF is expected to reduce emissions by 6.5%. This reduction expands to 31.4% by 2040, and by 2050, the adoption of

SAF could lead to a 60.8% decrease in CO_{2eq} emissions. The graph presented underscores the importance of SAF as a pivotal technology in the aviation industry's strategy to reduce greenhouse gas emissions. The increasing percentage reduction (in red) highlights the advancements in SAF production technologies and their integration into the aviation fuel supply chain. However, the rising total emissions indicate that SAF alone may not be sufficient to counteract the emissions growth driven by increased air traffic. The data from this graph provides a clear message: achieving substantial emissions reductions in aviation will require concerted efforts across multiple fronts, with SAF playing a leading role in this multifaceted strategy.

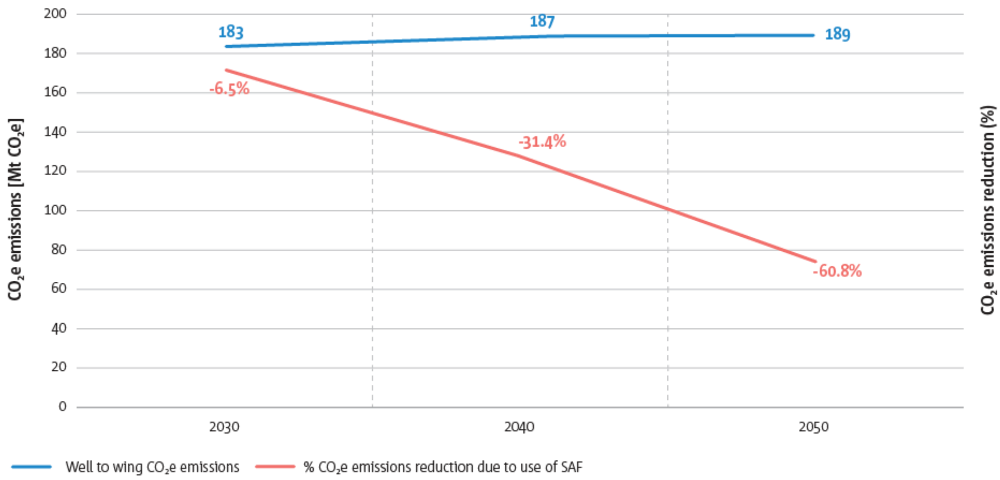

Figure 15 - Estimated CO_2eq emissions (megaton) and SAF reduction potential (%) according to the ReFuelEU proposal (EASA, 2022)

2.2. SAF: Policy Developments and investment trend

2.2.1. SAF policy landscape future

By 2030, significant policy developments are expected to support the scaling up SAF production and drive his adoption. Governments must implement policies that incentivize SAF production and use, such as blending mandates, subsidies, and tax credits. These policies should create a stable and predictable regulatory environment, encouraging investment in SAF technologies and infrastructure. The European Commission's "Fit for 55" package, introduced in July 2021, aims to boost the production and uptake of SAF through the ReFuelEU proposal. This proposal includes a blending mandate requiring aviation fuel suppliers to ensure that all aviation fuel supplied to aircraft operators at EU airports contains a minimum share of SAF, starting at 2% in 2025 and increasing to 6% by 2030 and 70% by 2050. The mandate also specifies that a portion of this SAF must be synthetic aviation fuel (PtL technology). Additionally, over 2000 companies, including 20 of the top 25 airlines, have signed up for net-zero targets, demonstrating a strong industry commitment to reducing emissions. The International Civil Aviation Organization (ICAO) has also set a goal of 5% emissions reduction by 2030.

Key policy developments by 2030 also include the introduction of national SAF roadmaps, which outline specific targets and actions for SAF adoption. International cooperation will be essential to harmonize standards and facilitate the global trade of SAF. Multilateral agreements, such as the

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), will play a critical role in setting global standards and promoting SAF use.

Looking ahead to 2050, the policy landscape will evolve to further support the widespread adoption of SAF. The EU's (REGULATION (EU) 2023/2405) targets include shares of SAF of 70% by 2050, with at least 35% consisting of synthetic aviation fuels of non-biological origin (in this report also named PtL pathway). This regulation underscores the importance of advancing synthetic fuel technologies to meet future demand sustainably. This ambitious target reflects the EU's commitment to achieving significant carbon reductions in the aviation sector. Several European countries are already considering introducing fuel taxes, ticket taxes, or a combination of both for the aviation sector to further incentivize the use of SAF.

Market prices for SAF are likely to remain higher than those for fossil jet fuel, making regulatory policy and incentives crucial for price competitiveness. The production costs of PtL fuels are projected to decrease significantly by 2050. According to a study published by Sustainable Energy & Fuels (2023), the cost of PtL-SAF in Europe could be around 0.81 EUR per litre, which translates to approximately 1,000 EUR per tonne by 2050. Another estimate from McKinsey & Company (2022) suggests that the cost could range between 676 EUR and 800 EUR per tonne by 2050. Additionally, Bauhaus Luftfahrt (2022) projects long-term PtL fuel production costs to be between 1170 and 1740 EUR per tonne. To bridge this cost gap, governments could implement mechanisms such as carbon pricing, subsidies, and tax credits to lower the effective price of SAF for airlines. These policies, along with international collaboration and harmonization of standards, will be crucial for achieving the ambitious targets set for 2050.

2.2.2. Investments in the SAF production market

Investment in SAF by 2030 will focus on expanding production facilities, improving supply chain logistics, and enhancing the efficiency of existing technologies. Governments and private investors will need to collaborate closely, with financial incentives like subsidies, tax credits, and grants playing a crucial role in stimulating investment. Public-private partnerships will be essential for sharing risks and benefits, ensuring that the necessary financial resources are mobilized to support the growth of the SAF sector. As shown in Figure 16, the global SAF market is expected to reach around 13,6 million EUR by 2032, a growth of 42.39% from 2023 to 2032, according to Precedence Research. (2023). Continuous advancements in technology, significant infrastructural investments, and robust market mechanisms will be required to ensure that SAF is both affordable and widely available. Furthermore, investment in research and development (R&D) will be essential to overcome technical challenges and reduce production costs. Governments, academic institutions, and private companies must collaborate on R&D initiatives, focusing on improving feedstock conversion efficiencies, discovering new feedstocks, and optimizing refining processes. Looking ahead, as highlighted in WP3, significant investments in the SAF market will be essential for scaling up production, particularly through public-private partnerships and research and development efforts

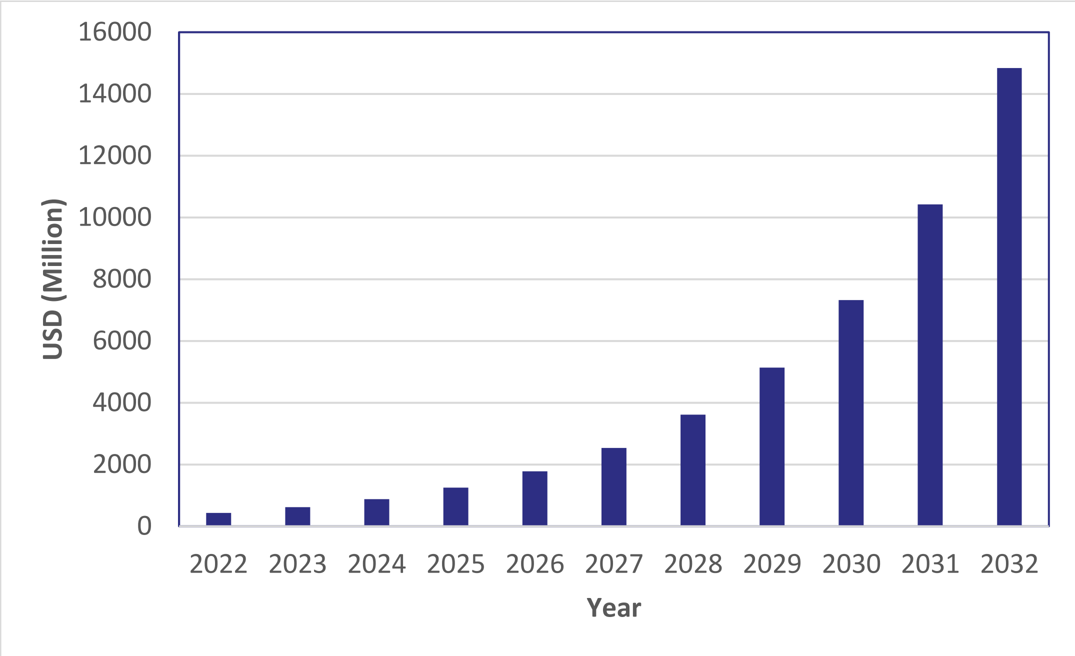

Figure 16 - SAF Market from 2022 to 2032 adapted from Precedence Research (2023).

2.3. Market participation and adoption of SAF by airlines and airports

The future market participation and adoption of SAF by aviation companies will be pivotal to achieve sustainability goals. By 2030, it is expected that a significant number of airlines will have integrated SAF into their fuel mix, driven by regulatory mandates, corporate sustainability commitments, and consumer demand for greener travel options.

By 2050, the goal is for SAF to be a mainstream fuel option, with widespread adoption across the aviation industry. Airlines will need to make long-term commitments to purchasing SAF, which will provide the market stability necessary for producers to scale up production. According to IATA, 43 airlines around the world have SAF voluntary commitments/agreements, which corresponds to 13 megatonnes (3.8% of global fuel demand) of SAF by 2030, as can be seen in the figure below.

Figure 17 - Airline Commitments by 2030 according to IATA (2024b).

Airlines and airports play a crucial role in the adoption and integration of SAF. By 2030, many major airlines are expected to have established SAF usage as part of their sustainability strategies. Airports will need to invest in infrastructure to support SAF distribution and storage, including dedicated storage tanks and blending facilities.

Collaborations between airlines and airports will be essential to streamline SAF logistics and ensure a seamless integration into the existing fuel supply chain. Joint initiatives, such as co-financing SAF production facilities and developing shared infrastructure, can help reduce costs and enhance supply chain efficiency.

By 2050, the goal is for SAF to be widely available at airports around the world, with robust infrastructure supporting its distribution and use. Airlines will have integrated SAF into their operations, contributing significantly to the reduction of aviation emissions and supporting global sustainability targets.

As outlined in WP4 from ICARUS, the development of best practices and concepts for scaling up SAF production will be essential to streamline market adoption and ensure long-term sustainability.

2.4. Research and development

Several companies have also started funding R&D activities related to Aviation decarbonization. This is the case for Emirates, which created an equivalent of 183 M EUR fund focused on SAF production technologies, and United Airlines, which created also a 183 M EUR venture fund, partnering with several entities, to support SAF production and Innovative technology (Emirates, 2023; United Airlines Ventures, 2024). However, more effort should be made to grant more funding for the aviation in groundbreaking technologies. The European Innovation Council (EIC) impart report from 2023 states that, since 2021, 4 projects related to Aviation & Airports were funded, when the total program funded 415 projects to accelerate the scale-up of novel innovations (European Innovation Council, 2024).

2.5. Set future goals to enhance the VC

Setting clear, ambitious goals is essential to drive the development and adoption of sustainable aviation fuel (SAF) and to ensure the entire value chain (VC) is aligned towards achieving these targets.

Future goals should address various aspects of the SAF supply chain, including production, consumption, investment, environmental impact, and policy support.

One of the primary objectives of increasing SAF usage is to reduce greenhouse gas (GHG) emissions. By 2030, the aviation industry should aim for a 5% reduction in emissions compared to 2020 levels. By 2050, the goal should be to achieve net-zero emissions, significantly contributing to global climate targets.

By 2030, the goal should be to scale up SAF production to meet at least 5% of the total aviation fuel demand in the EU, which equates to approximately 2.3 million tonnes. This requires increasing the current production capacity significantly, from the current 0.24 million tonnes to at least 2.3 million tonnes. By 2050, the goal should be even more ambitious, targeting 70% SAF usage in aviation fuel, which a minimum share of a minimum share of 35 % of advanced biofuels and 35% of renewable fuels of non-biological origin (RFNBO), as shown in Figure 18.

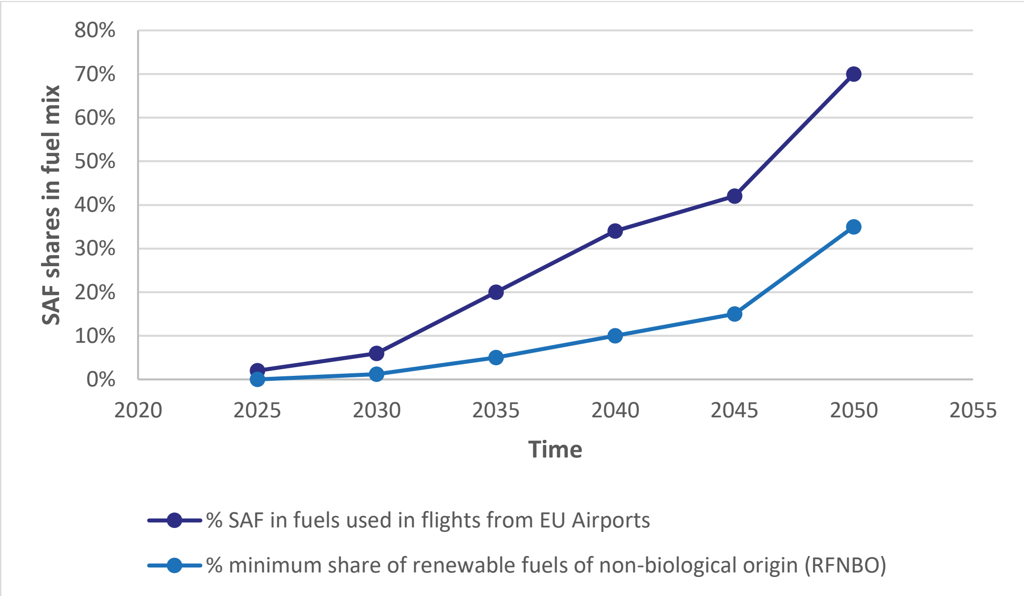

Figure 18 - Net-Zero target for international aviation leaving EU airports.

Airlines should aim to progressively increase their consumption of SAF. By 2030, in EU airlines should target a minimum of 6% SAF in their total fuel consumption, supported by blending mandates and incentives. By 2050, this target should rise to 70%, reflecting the anticipated advancements in SAF production technologies and increased availability.

Substantial investment is required to achieve the production and consumption targets. By 2030, governments and private sector stakeholders should aim to mobilize investments amounting to several billion dollars to support R&D, infrastructure development, and scaling up of SAF production facilities. By 2050, cumulative investments should reach a level that ensures the full commercialization and widespread availability of SAF.

Policymakers should continue to enhance and implement supportive regulations and incentives. By 2030, there should be a comprehensive policy framework across major aviation markets that includes SAF blending mandates, tax credits, subsidies, and R&D funding. By 2050, policies should be fully harmonized internationally, ensuring a level playing field and maximizing the global impact of SAF.

Collaboration across the SAF value chain is critical. By 2030, the goal should be to establish strong partnerships among feedstock suppliers, technology providers, fuel producers, airlines, and regulatory bodies. Innovation goals should focus on advancing emerging technologies such as PtL fuels, and other advanced biofuel technologies. By 2050, the objective should be to achieve technological breakthroughs that make SAF production more efficient, cost-effective, and scalable.

To support the increased production and consumption of SAF, substantial infrastructure development is needed. By 2030, the goal should be to upgrade existing facilities and build new infrastructure for SAF production, storage, and distribution. Major airports should have dedicated SAF storage tanks and refuelling systems in place. By 2050, the entire aviation fuel infrastructure should be capable of handling a high percentage of SAF, ensuring seamless integration into the existing supply chain.

A robust monitoring and evaluation framework is essential to track progress towards these goals. By 2030, industry stakeholders should establish clear performance metrics and regular review processes to assess progress. By 2050, these frameworks should be fully integrated, providing real-time data and insights to guide decision-making and ensure the achievement of long-term targets.

By setting and striving to achieve these future goals, the aviation industry can significantly enhance the SAF value chain, driving the transition to sustainable aviation and contributing to global efforts to mitigate climate change.

3. Concluding remarks

The current report outlines the comprehensive steps and strategies needed to address the identified gaps, proposing detailed solutions and recommendations to facilitate a smooth transition for the desired state of the SAF supply chain.

It is essential to identify the specific areas where improvements are needed. These gaps can be broadly categorized into technological, economic, financial, policy, regulatory, market, and supply chain domains.

In terms of **technological gaps**, current SAF production technologies may not be efficient or scalable enough to meet future demands. To address this, it is vital to invest in research and development (R&D) to develop advanced SAF production technologies at lower costs. This includes improving conversion efficiencies, discovering new feedstocks, and optimizing refining processes. For instance, advancements in HEFA technology can significantly enhance production efficiency, if new sustainable oils sources will be available in EU and worldwide. Additionally, implementing pilot projects to test and validate new emerging technologies allows for real-world evaluation and iterative improvements, ensuring the scalability of these innovations. Collaborating with academic institutions and research organizations can also accelerate technological advancements by pooling expertise and resources. Moreover, establishing innovation hubs and incubators focused on SAF technology can provide startups and small enterprises with the necessary support to bring their innovations to market.

Economic and financial gaps present significant barriers, primarily due to the high cost of SAF production and the limited availability of feedstock. To mitigate these issues, governments should provide financial incentives such as subsidies and tax credits to lower production costs and encourage investment in SAF infrastructure. An example of this could be the introduction of a tax credit for every litre of SAF produced, like the U.S. biodiesel tax credit, which has successfully stimulated production in the renewable fuel industry. Furthermore, fostering public-private partnerships can share risks and benefits, boosting investment in SAF production. For example, a partnership between a government agency and private companies could finance a new SAF production facility, combining public funding with private expertise and resources. Additionally, establishing green investment funds and offering low-interest loans can attract private investors and financial institutions to support SAF projects.

Policy and regulatory gaps also need to be addressed. Inconsistent policies and regulations across regions can hinder the widespread adoption of SAF. Therefore, developing and implementing harmonized regulations that support SAF production and use across different regions is crucial. International agreements and national policies should align to create a consistent and supportive regulatory environment. For instance, the European Union's Renewable Energy Directive (RED) could serve as a model for creating a cohesive policy framework that promotes the use of SAF across member states. Additionally, introducing blending mandates that require a certain percentage of SAF to be mixed with conventional jet fuel can drive demand and provide market certainty for SAF producers. For example, the EU mandate requiring a 6% SAF blend in all jet fuel by 2030 could significantly boost production and investment in SAF. Furthermore, establishing clear and transparent certification processes for SAF can ensure compliance with sustainability standards and build consumer confidence.

Addressing **market and supply chain gaps** involves investing in the necessary infrastructure to support the production, storage, and distribution of SAF. This includes upgrading existing facilities and constructing new ones where necessary. For instance, building dedicated SAF storage tanks at major airports can facilitate the seamless integration of SAF into the existing fuel supply chain. Enhancing collaboration among key stakeholders in the SAF value chain, including feedstock suppliers, technology providers, fuel producers, airlines, and government bodies, is also essential. Joint ventures and partnerships can leverage the strengths of multiple entities to accelerate SAF production and distribution. For example, a collaboration between a major airline and a leading SAF producer could result in a long-term supply agreement, ensuring a steady demand for SAF and providing financial stability for the producer. Additionally, developing regional SAF hubs can centralize production and distribution, reducing logistical challenges and costs.

Following these steps will foster the development of SAF, contributing significantly to the reduction of the aviation industry's carbon footprint and supporting the transition to a more sustainable future. By addressing technological, economic, financial, policy, regulatory, market, and supply chain gaps, the ICARUS project can pave the way for a robust and resilient SAF supply chain, ensuring long-term environmental and economic benefits.

At last, but not the least, the development of an action plan is critical for bridging the current gaps in SAF production and guiding the ICARUS project towards its long-term goals of scaling SAF production and addressing current market challenges. WP4 will play a key role in this process. WP4 will provide insights into the best practices for SAF upscaling, certification processes, and stakeholder engagement, especially with key actors like airlines and airports. This action plan will be responsive to these findings, ensuring that the strategies proposed here remain aligned with the evolving market landscape and technological innovations. By the end of the ICARUS project, WP4 will deliver crucial recommendations and strategies that will feed directly into this action plan, providing concrete steps for scaling SAF production and ensuring its long-term sustainability.”

To ensure the successful implementation of the action plan, a robust monitoring and evaluation framework should also be established. This framework should include clear performance metrics to assess progress towards closing the identified gaps. Regular reviews and audits can evaluate the effectiveness of the implemented strategies and make necessary adjustments. Additionally, maintaining continuous engagement with all stakeholders is crucial to gather feedback, address concerns, and ensure alignment with the overall objectives. Implementing digital tracking systems can enhance transparency and provide real-time data on SAF production and distribution, facilitating informed decision-making and timely interventions.

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