Decarbonization of the Aviation Sector: Current Status, Challenges, and Future Outlook

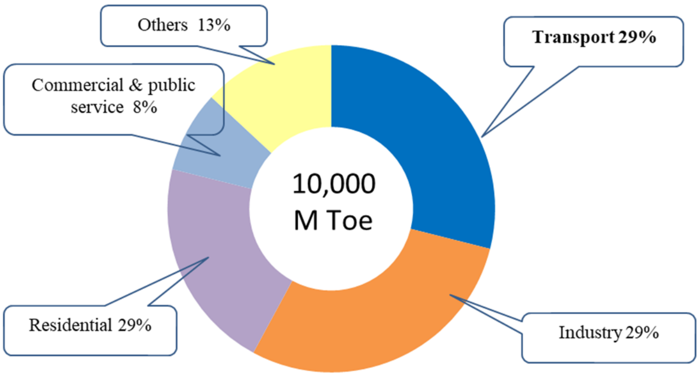
*Masato Yoshida

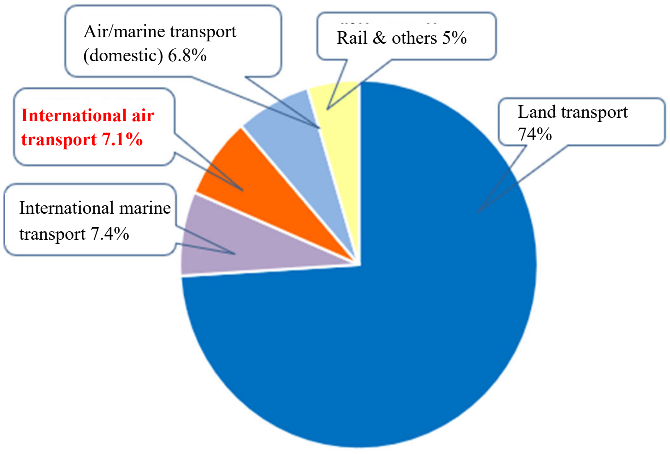
Introduction

The aviation sector is known to be one of the “hardest-to-abate” sectors alongside the steel and heavy industries. Governments are taking various actions to decarbonize their industrial sectors in order to achieve their GHG emissions reduction targets. In the international aviation sector, however, efforts have lagged behind due to the complexities of crossing national borders, difficulty of establishing a framework for international collaboration, and the limited options available. In response, efforts to introduce sustainable air fuels have been accelerating worldwide and are receiving much attention. This report summarizes the current situation surrounding sustainable aviation fuels, discusses the challenges for increasing their use, and analyzes the outlook.

1. Current Status of Decarbonization of the Aviation Sector

First, let’s consider the current situation of decarbonizing the aviation sector. **Figure 1-1** below shows the final energy consumption of the world as a whole and the share by sector, and **Figure 1-2** shows the breakdown of final energy consumption in the transportation sector. The world’s final energy consumption was 10 billion tonnes of oil equivalent in 2019, of which the transportation sector accounted for 29%. In this sector, land transport was the largest energy consumer with 74%, while international air transport accounted for 7.1%. In short, **on a global basis, air transport accounts for approximately 2.0% of final energy consumption and thus its impact is relatively small.**





Source: Prepared by the author based on the IEA World Energy Statistics and Balances (July 2021)

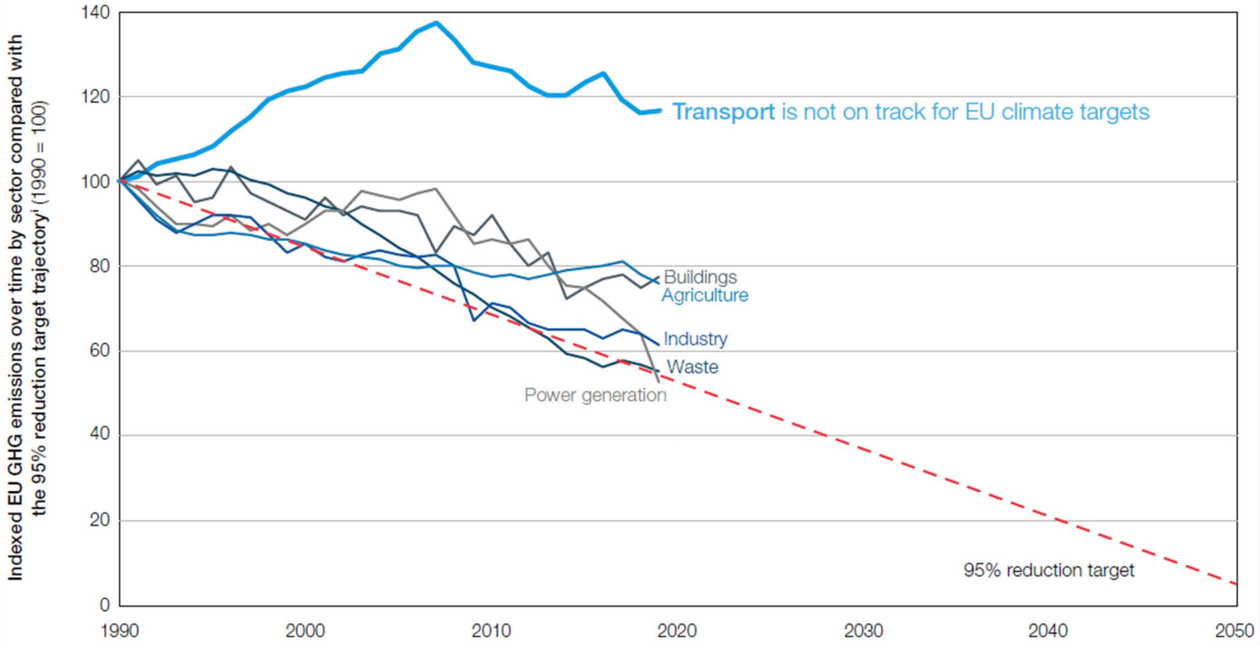
Figure 1-1 Final energy consumption by sector (2019)

Figure 1-2 Breakdown of final energy consumption in the transportation sector (2019)

---

*Senior Researcher, New Energy System Group, Electric Power Industry & New and Renewable Energy Unit

The reason for the increasing attention on decarbonizing the aviation sector, despite its relatively small impact, is the sheer difficulty of reducing its GHG emissions. **Figure 1-3** below compares the GHG emissions of the European Union (EU) by sector with the EU's target trajectory for GHG emissions reduction (a 95% reduction by 2050). Unlike the significant progress of reducing GHG emissions in the power generation, industry, agriculture, and building sectors, the transportation sector deviates sharply from the ideal path. The chart shows that decarbonizing the transportation sector is difficult even for the EU, which has voluntarily introduced strict guidelines and acted early.



Source: World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation[1] (November 2020) (Original source: European Federation for Transport and Environment)

Figure 1-3 Changes in the EU's GHG emissions by sector (compared with the 2050 target trajectory; 1990 = 100)

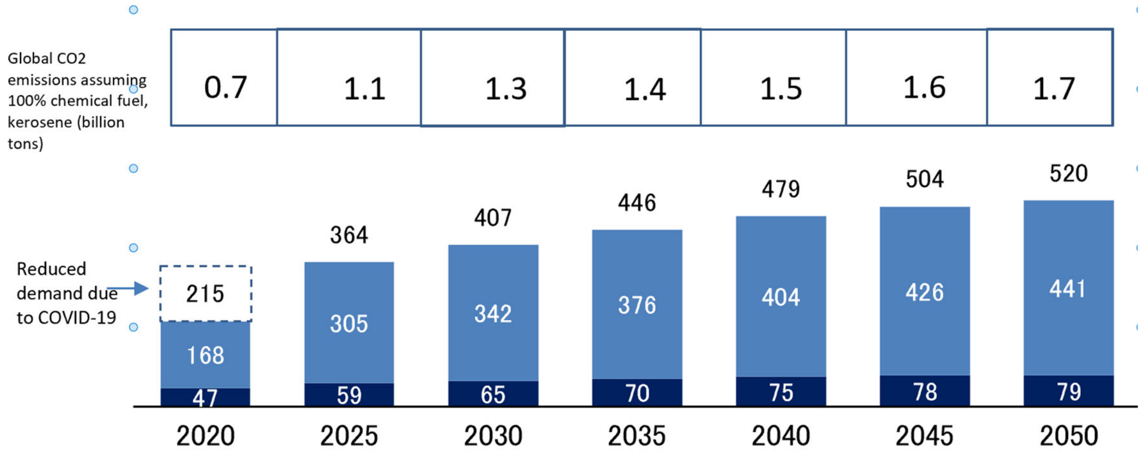
As such, European countries are already shifting the focus of their decarbonization efforts to the aviation sector. This has happened mainly because the aviation industry, despite having experienced a temporary pandemic-induced drop in demand, is expected to continue to post high growth in line with global economic growth and thus generate more CO_2 emissions[2] (**Figure 1-4**); the transport sector, including aviation, is considered to be more costly to decarbonize than others[3] despite having a great emissions reduction potential because efforts have been put on the back burner until now (**Figure 1-5**); it is essential to establish an internationally coordinated legislative framework but adjustments will take time; and it will be a long time before innovative technologies to reduce emissions for aircraft, even if developed, are commercialized and start producing effects because passenger aircraft have an extremely long upgrade cycle of around 25 years.

---

[11] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, World Economic Forum, p.7

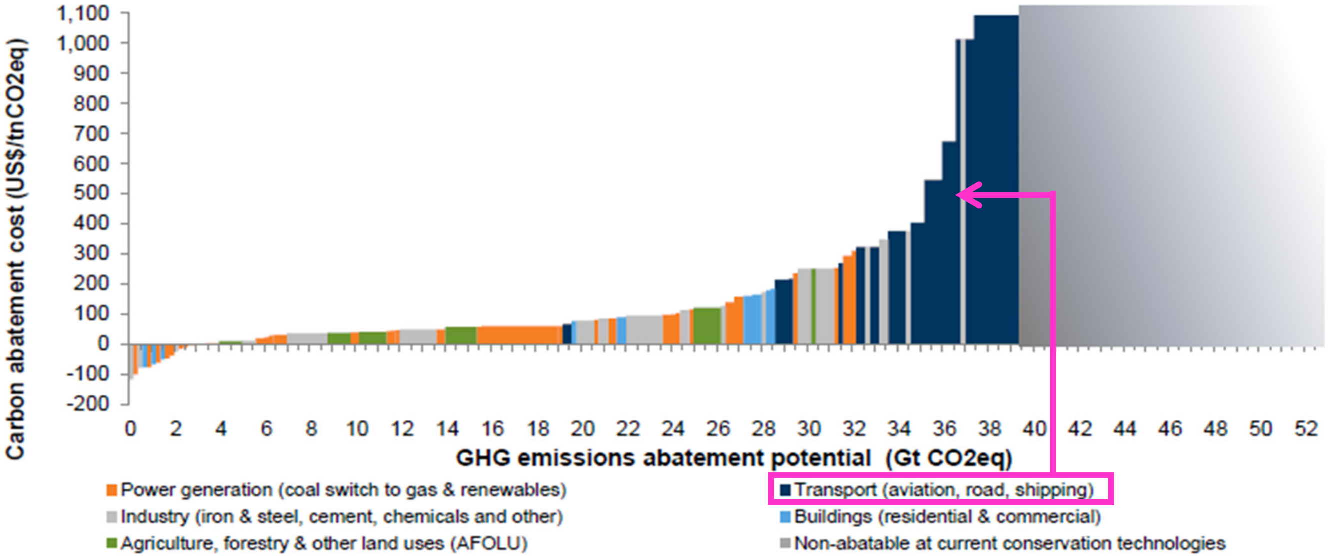
[2] *Ibid*., p.8

[3] The aviation sector has a great emissions reduction potential but is estimated to cost at least five times more to decarbonize than the power generation and agricultural sectors, Goldman Sachs Global Investment Research (December 11, 2019), "Carbonomics: The Future of Energy in the Age of Climate Change," https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-f/report.pdf



Note: Assumed to emit 3.15 ton-CO_2 per tonne of fossil-based kerosene.
Source: Prepared by the author based on World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation[4] (November 2020) (Original source: Energy Insight's Global Energy Perspective, Reference Case A3 October 2020; IATA; ICAO)

Figure 1-4 Outlook for global aviation fuel demand (till 2050; millions of tonnes/year)



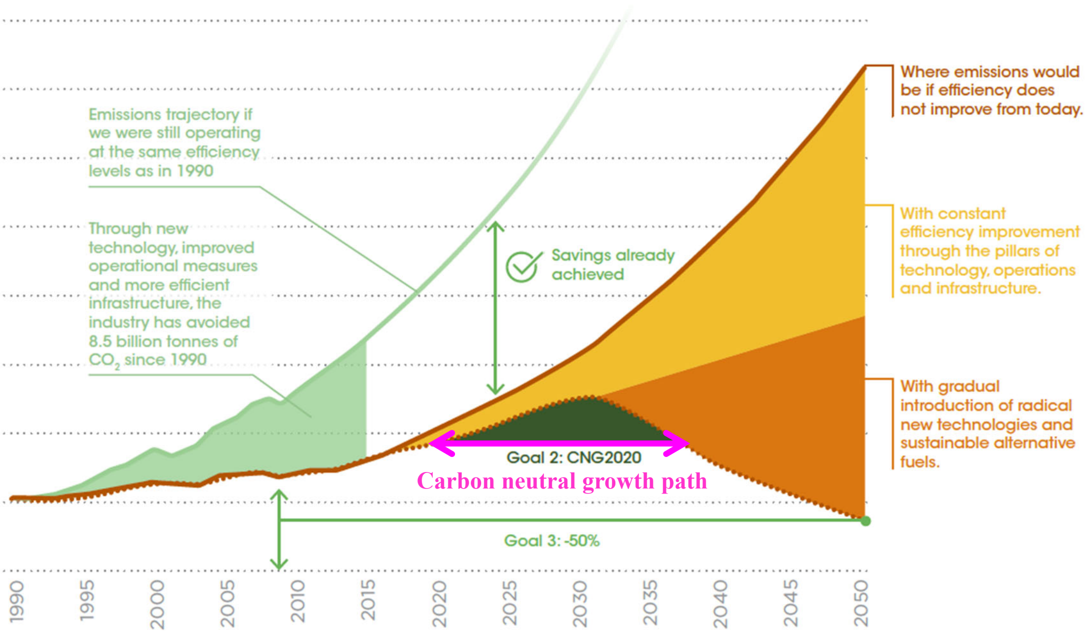
Source: Goldman Sachs Global Investment Research (December 11, 2019)

Figure 1-5 GHG emissions reduction potential and CO_2 emissions reduction cost (based on currently available technologies)

The aviation sector is making its own efforts to reduce GHG emissions. While the sector is outside the scope of the Paris Agreement, the member states of the International Civil Aviation Organization (ICAO) have ratified the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and are working toward achieving a path of carbon neutral growth (CNG) in 2020 and beyond (**Figure 1-6**).

---

[4] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation*, Swiss: World Economic Forum, p.7



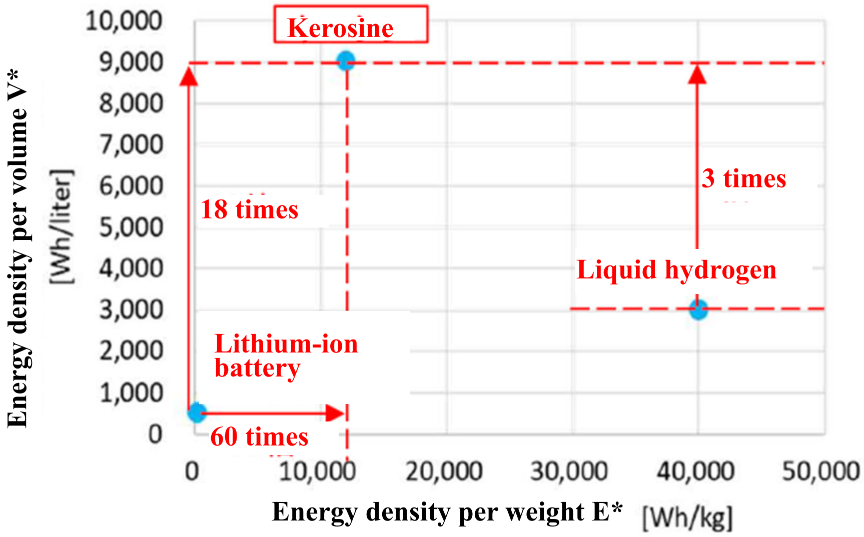
Source: IRENA (July 2021)[5], with information added by the author

Figure 1-6 Roadmap for reducing GHG emissions in the aviation sector

Sustainable aviation fuel (SAF) is currently receiving increasing attention as a CORSIA-compliant GHG emissions reduction technology. Fossil fuel-sourced kerosene, or jet fuel which is currently used as aviation fuel, is an excellent fuel in terms of both volumetric energy density and mass energy density (**Figure 1-7**). To decarbonize the aviation sector, it is necessary to replace jet fuel with liquid fuels that have the same properties, or to electrify the power source or adopt fuel cells or hydrogen engines (**Figure 1-7**). However, the latter involves various issues. First, to shift to electricity as the power source, it will be essential to electrify long-haul flights of more than 1,500 km, which account for more than 80% of the GHG emissions of the aviation sector, which will require batteries with an extremely high energy density. However, it is difficult to significantly increase the battery energy density with currently available technologies, and so even if electricity is adopted, it will initially only be used for short- to medium-haul flights (of up to 1,000 km). Hydrogen is considered to be promising for fuel cells and hydrogen direct combustion engines as liquid hydrogen has an extremely high mass energy density of three times that of jet fuel; however, fuel cells that can support flights of over 2,000 km are unlikely to become commercially available until the 2040s. France's Airbus is developing a hydrogen direct combustion engine for aircraft for long-haul flights of over 2,000 km, but its commercial launch is not likely to happen until 2035 at the earliest. Therefore, **for the next 10 to 15 years, SAF is the only realistic option with an energy efficiency equivalent to that of jet fuel** (**Figure 1-8**).

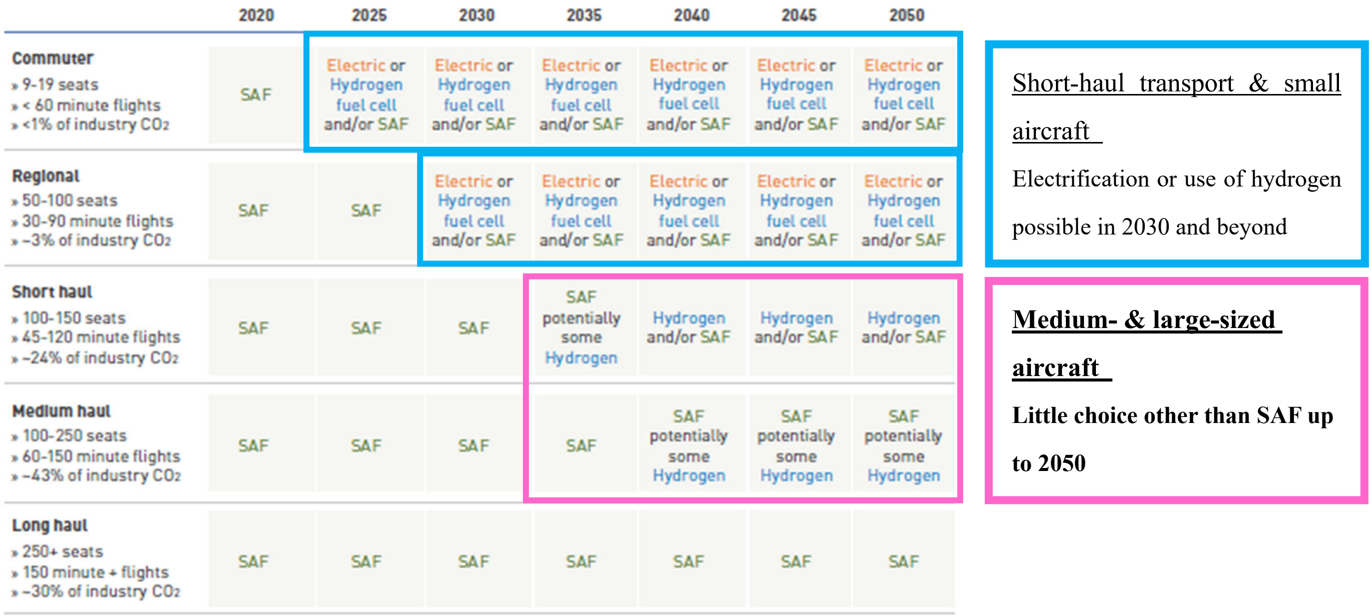
---

[5] IRENA (July 2021), *Reaching Zero with Renewables: Biojet Fuels*, Abu Dhabi: International Renewable Energy Agency, p.19



Source: Ministry of Land, Infrastructure and Transport and Tourism (Original source: Electric Flight – Potential and Limitations, Institute of Aerodynamics and Flow Technology, Martin Hepperle, German Aerospace Center)[6]

Figure 1-7 Comparison of volumetric energy density and mass energy density of aviation fuel



	2020	2025	2030	2035	2040	2045	2050
Commuter » 9-19 seats » < 60 minute flights » <1% of industry CO_2	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Regional » 50-100 seats » 30-90 minute flights » ~3% of industry CO_2	SAF	SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF	Electric or Hydrogen fuel cell and/or SAF
Short haul » 100-150 seats » 45-120 minute flights » ~24% of industry CO_2	SAF	SAF	SAF	SAF potentially some Hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium haul » 100-250 seats » 60-150 minute flights » ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF potentially some Hydrogen	SAF potentially some Hydrogen	SAF potentially some Hydrogen
Long haul » 250+ seats » 150 minute + flights » ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Short-haul transport & small aircraft

Electrification or use of hydrogen possible in 2030 and beyond

Medium- & large-sized aircraft

Little choice other than SAF up to 2050

Source: Waypoint 2050 (ATAG, September 2021)[7], with information added by the author

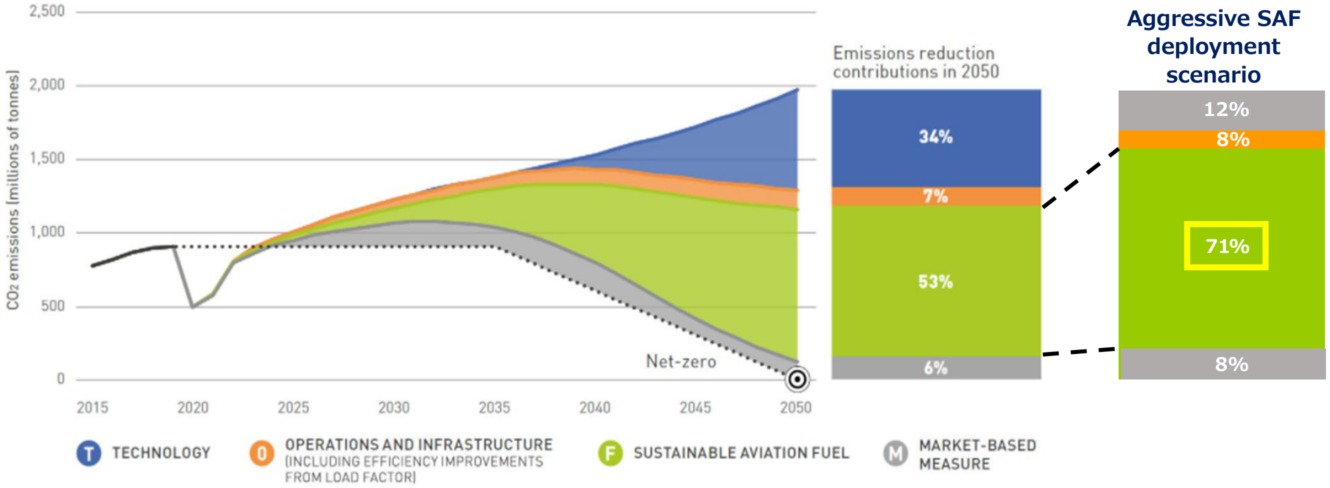
Figure 1-8 Outlook for introducing technologies to decarbonize aircraft

The Air Transport Action Group (ATAG) is considering various scenarios for achieving net-zero emissions in the aviation sector by 2050. As for SAF's contribution to GHG reduction as of 2050, the ATAG estimates that SAF will account for 53% of the reduction under the advanced technology scenario and for 71% under the aggressive SAF deployment scenario (**Figure 1-9**).

---

[6] Civil Aviation Bureau, Ministry of Land, Infrastructure, Transport and Tourism (March 22, 2021), First Study Group on Reducing CO_2 in the Aviation Operation Sector

[7] ATAG (September 2021), *Waypoint 2050*, Swiss: Air Transport Action Group, p.54



Source: Waypoint 2050 (ATAG), p.26 with information added by the author

Figure 1-9 Roadmap for reducing GHG emissions in the aviation sector

European countries and the United States have made a head start and have already set policy goals to accelerate the introduction of SAF (**Table 1-1**). Japan is also considering setting a target to supply 10% of aviation fuel demand with SAF by 2030.[8]

Table 1-1 National and regional government targets for introducing SAF

Country / region	SAF introduction targets and mandates
🇪🇺	Introduction of SAF promoted through the ReFuelEU Aviation Initiative (SAF blending mandate proposed for EU airports: 5% in 2030, 38% in 2040, 63% in 2050)
🇫🇷	A roadmap for accelerating SAF introduction has been formulated (2% in 2025, 5% in 2030) * Focusing on advanced feedstocks
🇳🇴	0.5% SAF blending mandate in place (from 2020), discussions under way on raising it to 30% in 2030.
🇫🇮	A policy in place to gradually increase the SAF blending mandate to 30% in 2030.
🇸🇪	A bill has been submitted to gradually increase the SAF blending mandate to 30% in 2030.
🇩🇪	Anticipates a mandatory SAF quota of 2% in 2030. * Power-to-liquid kerosene only
🇳🇱	A SAF roadmap that includes blending mandates is being formulated. * Focusing on advanced feedstocks
🇪🇸	A SAF blending mandate of 2% in 2025 in place (Climate Change Law) * Focusing on wastes and residues
🇺🇸	Replace all aviation sector air fuels (both military and non-military) with SAF by 2050. Aim for a 20% reduction of CO_2 emissions from the aviation sector by 2030 and produce and supply 3 billion gallons of SAF in 2 years. To achieve these goals, plans to introduce tax breaks have been announced.

Source: Prepared by the author based on the press releases, etc.[9] of various national and regional governments

---

[8] The Nikkei (February 15, 2022), "Decarbonize the skies: Government sets target to supply 10% of aviation fuel demand with renewable fuels," https://www.nikkei.com/article/DGXZQOUA089TK0Y2A200C2000000/

[9] Introduction of tax break for the US SAF blending operators: Reuters (April 14, 2022), "Biden renews push for sustainable aviation fuel tax credit," https://www.reuters.com/business/energy/biden-renews-push-sustainable-aviation-fuel-tax-credit-2022-04-12/

An overview of decarbonizing the skies has been described so far. The next chapter examines the basic properties, production technologies, and raw materials of SAF, as well as an overview of its current supply and demand and the future outlook.

2. Sustainable Aviation Fuels (SAF)

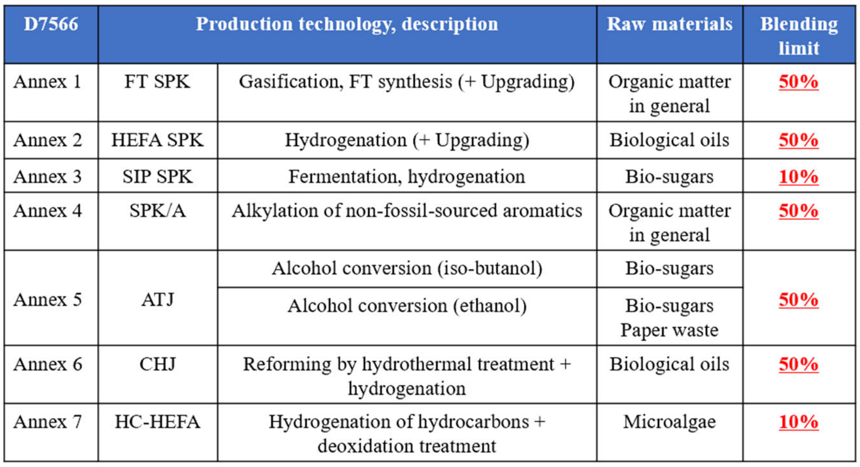
(1) What is SAF?

SAF is an aviation fuel produced using biomass, wastes such as waste cooking oil and municipal garbage, and carbon, hydrogen, etc. contained in exhaust gases as raw materials. It functions like kerosene but is estimated to emit 60–80% less CO_2 compared to fossil-based fuels. The International Air Transport Association (IATA) defines SAF as "a fuel for aviation with non-fossil sources, an aviation fuel that is sustainable and produced from alternative feedstock to crude oil."[10] The ICAO defines SAF as "**fuels that have a potential to be sustainably produced and to generate lower carbon emissions than conventional kerosene on a life cycle basis.**"[11] This report will adopt the ICAO's definition in its analysis.

(2) International standards for SAF and CORSIA's criteria for sustainability

ASTM International categorizes and certifies the international standards for SAFs based on their production technology and raw materials in Annex 1 to 6 of its ASTM D7566 (**Table 2-1**). When a SAF is produced by one of the certified technologies and satisfies the properties specified by ASTM, the blended fuel produced by mixing SAF with jet fuel (maximum blending ratio of 50%) is recognized as satisfying the international jet fuel standards (ASTM D1655), making any additional safety measures or infrastructure modifications unnecessary.

Table 2-1 International standards for SAF (ASTM D7566 Annex)



D7566	Production technology, description		Raw materials	Blending limit
Annex 1	FT SPK	Gasification, FT synthesis (+ Upgrading)	Organic matter in general	**50%**
Annex 2	HEFA SPK	Hydrogenation (+ Upgrading)	Biological oils	**50%**
Annex 3	SIP SPK	Fermentation, hydrogenation	Bio-sugars	**10%**
Annex 4	SPK/A	Alkylation of non-fossil-sourced aromatics	Organic matter in general	**50%**
Annex 5	ATJ	Alcohol conversion (iso-butanol)	Bio-sugars	**50%**
		Alcohol conversion (ethanol)	Bio-sugars Paper waste	
Annex 6	CHJ	Reforming by hydrothermal treatment + hydrogenation	Biological oils	**50%**
Annex 7	HC-HEFA	Hydrogenation of hydrocarbons + deoxidation treatment	Microalgae	**10%**

Source: Prepared by the author based on IEA Bioenergy[12] and others

---

[10] IATA, "What is SAF?," https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-what-is-saf.pdf

[11] ICAO, "Alternative Fuels: Questions and Answers," https://www.icao.int/environmental-protection/Pages/AltFuel-SustainableAltFuels.aspx#:~:text=WHAT%20ARE%20SUSTAINABLE%20ALTERNATIVE%20JET,on%20a%20life%20cycle%20basis.

[12] IEA Bioenergy (May 2021), *Progress in Commercialization of Biojet/Sustainable Aviation Fuel (SAF): Technologies, potential and challenges*, IEA Bioenergy Task 39, France: International Energy Agency, pp.13-16

In order for SAF to be used as fuel for international flights, in addition to meeting the ASTM standards, the SAF manufacturer must obtain traceability certification approved by the ICAO’s Sustainable Certification Schemes (SCS) as well as certification of compliance with CORSIA’s Sustainability Criteria for SAFs (**Table 2-2**).

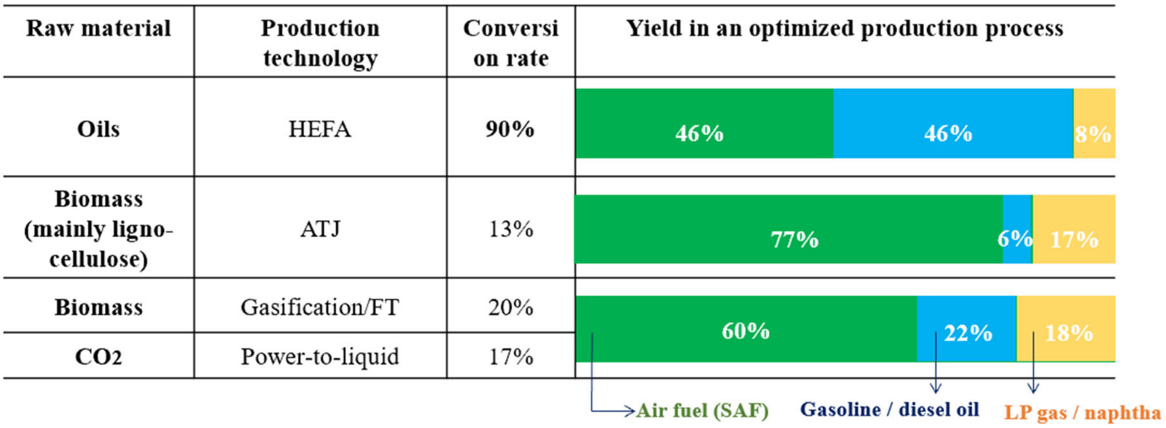
Table 2-2 CORSIA sustainability criteria for SAFs

GHG gases	**Principle**	CORSIA-eligible fuel shall generate lower carbon emissions on a life cycle basis.
	Criterion	Achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis (including induced land use change).
Carbon stock	**Principle**	CORSIA-eligible fuel shall not be made from biomass obtained from land with high carbon stock.
	Criterion 1	CORSIA-eligible fuel shall not be made from biomass obtained from land converted after January 1, 2018 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
	Criterion 2	・In the event of land use conversion after January 1, 2018, as defined based on IPCC land categories, direct land use change (DLUC) emissions shall be calculated. ・ If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value shall replace the default ILUC value.

Source: Prepared by the author based on CORSIA Sustainability Criteria for CORSIA Eligible Fuels (ICAO)[13]

(3) Production technologies: technological maturity, raw materials, and yield

As shown in **Table 2-1** above, seven SAF production technologies have obtained ASTM certification to date. Hydrotreated Eaters and Fatty Acids – Synthesized Paraffinic Kerosene (HEFA-SPK) described in Annex 2, a production technology in which biological oils are hydrogenated, is the most technologically mature and has already been launched commercially. By optimizing the production process to maximize the yield of SAF, the technology will be able to produce SAF equivalent to up to 46% of the raw material input (**Figure 2-1**).



Raw material	Production technology	Conversion rate	Yield in an optimized production process
Oils	HEFA	**90%**	46% / 46% / 8%
Biomass (mainly ligno-cellulose)	ATJ	13%	77% / 6% / 17%
Biomass	Gasification/FT	20%	60% / 22% / 18%
CO2	Power-to-liquid	17%	

Source: Prepared by the author based on: World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (November 2020) (Original source: McKinsey Global Energy Practice; ICCT; IRENA, etc.)

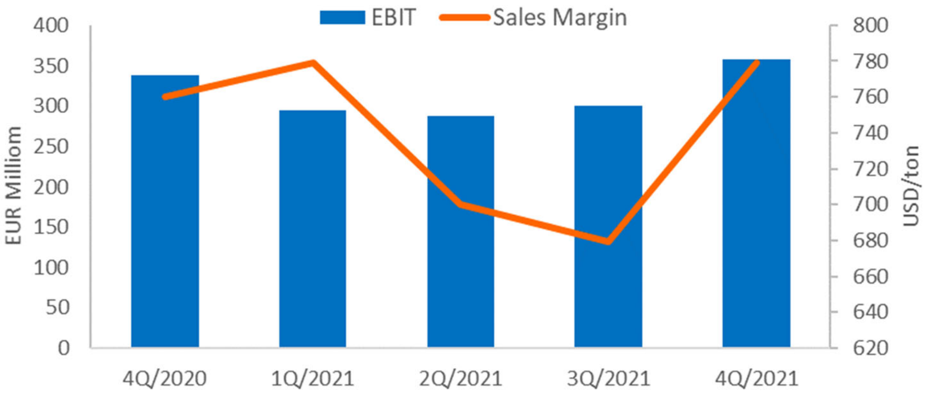
Figure 2-1 Comparison of yield of SAF products (by technology)

---

[13] ICAO (June 2019), *CORSIA Sustainability Criteria for CORSIA Eligible Fuels*, CANADA: International Civil Aviation Organization

(4) Supply and demand: Current situation and future outlook

The global supply of SAF was less than 50,000 tonnes in 2020 and is estimated to account for about 0.03% of the global aviation fuel demand. Nevertheless, a large number of SAF production and capacity expansion projects are under way worldwide on the back of strong demand, and SAF output is expected to rise sharply in the next few years. In particular, Finland's NESTE has one of the world's highest SAF supply capabilities, with plans to launch a SAF production plant (1 million tonnes/year) in Singapore in the first quarter of 2023 (**Table 2-3**). Further, the company's Renewable Products segment, which includes renewable diesel, has become a high-added-value business that consistently delivers 300 million euros in operating profit (EBIT) and 7 to 8 million US dollars/tonne in sales margin each quarter (**Figure 2-2**).



Note: NESTE's Renewable Products segment: Produces renewable diesel, SAF, renewable solvents, and bioplastics raw materials based on the company's own patented technology and sells them in domestic and international wholesale markets.
Source: Prepared by the author based on NESTE Annual Report 2021[14] and quarterly report[15]

Figure 2-2 NESTE's Renewable Products business: Quarterly operating profits (EBIT) and sales margin

Table 2-3 lists SAF manufacturers and their location, production technology, raw materials, and capacity. Some manufacturers' capacities are aggregated with renewable diesel, etc., making accurate analysis difficult, but in order to replace 10% of the world's current jet fuel demand (approximately 167 million tonnes) with SAF, 16 million tonnes of SAF will be required, and thus the current supply capacity is extremely small. HEFA-SPK is effectively the only SAF production technology that is commercially available, and is currently used by most SAF manufacturers for commercial production. Demonstration projects are under way worldwide for SAF production using FT-SPK and ATJ technologies but commercial launch is not expected until a few years later. Thus, to resolve any supply bottlenecks over the next five to ten years, further process optimization and increasing the SAF output from HEFA-SPK through technological breakthroughs will be key, assuming that SAF raw materials can be stably secured. Further, raw materials for SAF are distributed unevenly in different parts of the world, limiting the scale of SAF production at each location. Therefore, to secure a stable SAF supply, it is necessary to develop a system for distributing small quantities. Regarding the production and supply of SAF so far, the market has been driven by independent operators such as World Energy and

---

[14] https://www.neste.com/sites/neste.com/files/attachments/corporate/investors/corporate_governance/neste_annual_report_2021.pdf
[15] https://www.neste.com/investors/materials

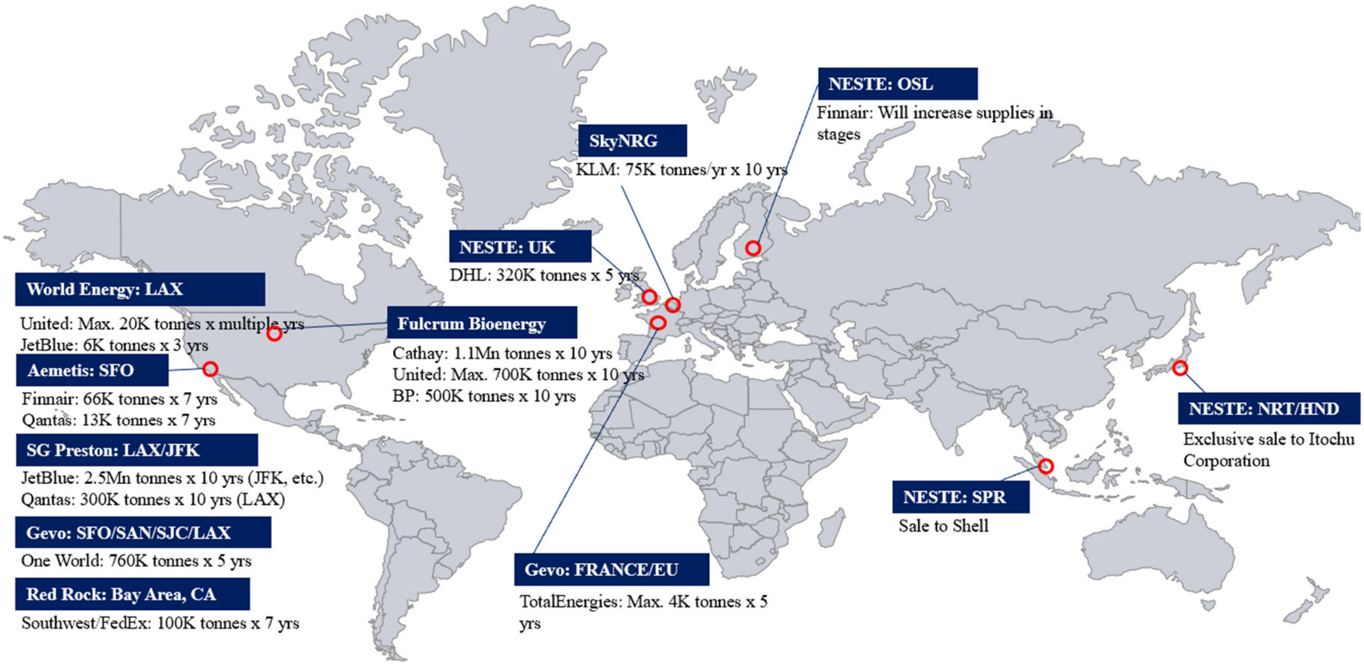
Finland's NESTE, which took the lead in focusing on the renewable products business. But recently, first- and second-tier oil majors such as France's TotalEnergies, Italy's ENI, and Spain's Repsol have entered the market. Because SAF is blended with jet fuel and is distributed via supply chains, it appears relatively easy for oil companies, which possess oil refining technologies, large plants, and established jet fuel supply chains, to capture market share from existing players.

Table 2-3 Summary of SAF supply

Producer	Location	Technology	Raw materials	Capacity (tonne/yr)
NESTE	Rotterdam (Netherlands)	HEFA	Plant oil, waste cooking oil, tallow	450,000
	Porvoo (Finland)	HEFA	Plant oil, waste cooking oil, tallow	100,000
	Delfzil (Netherlands)	HEFA	Plant oil, waste cooking oil, tallow	100,000
	Singapore (Singapore)	HEFA	Plant oil, waste cooking oil, tallow	1,000,000 (1Q, 2023)
World Energy	Paramount (US)	HEFA	Non-cooking oil, waste	570,000*
Diamond Green Diesel	Norco (Louisiana, US)	HEFA	Plant oil, tallow, waste cooking oil	1,500,000*
	Port Arthur (Texas, US)	HEFA	Plant oil, tallow, waste cooking oil	1,800,000 (2023)*
UPM	Lappeenranta (Finland)	HEFA	Crude tall oil	500,000*
Renewable Energy Group (Chevron)	Geismar (Louisiana, US)	HEFA	Free fatty acid	1,300,000 (2023)*
ST1	Gothenburg (Sweden)	HEFA	Tall oil	70,000
Preem	Gothenburg (Sweden)	HEFA	Tallow, raw tall oil	270,000 (2024)
TotalEnergies	La Mede (France)	HEFA	Waste cooking oil, plant oil	100,000
	Granpuits (France)	HEFA	Waste cooking oil, plant oil	170,000
ENI	Gela (Italy)	Ecofining	Waste cooking oil, fat	150,000 (2024)*
Repsol	Cartagena (Spain)	Co-processing	Plant oil	N.A.
	Purrtollano (Spain)	Co-processing	Plant oil	N.A.

Note 1: (*) Aggregate total with renewable diesel output Note 2: FT-SPK, ATJ, etc. and other technologies in demonstration stage not included
Source: Prepared by the author based on IRENA (July 2021), Argus Media, and websites and press releases of various companies

The most powerful drivers of SAF demand are airlines, air freight carriers, and oil companies. A large number of SAF trade contracts have been signed in recent years, and a framework for supplying SAF is gradually developing mainly in Europe and the United States (**Figure 2-3**).



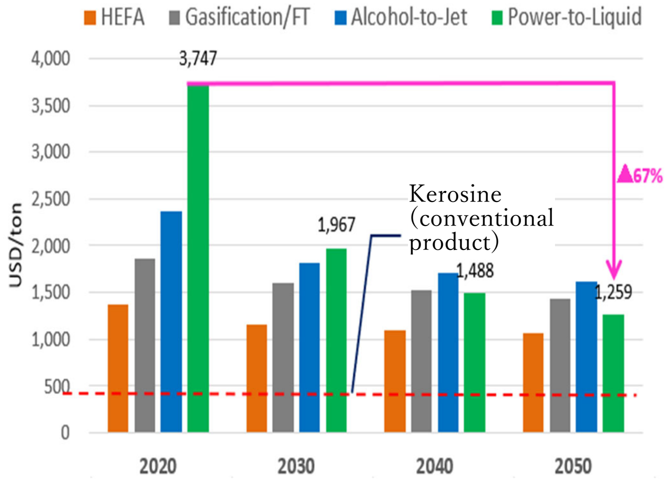
Source: Prepared by the author based on the State of Sustainable Aviation Fuel (SAF) (CAAFI), various corporate press releases, etc.

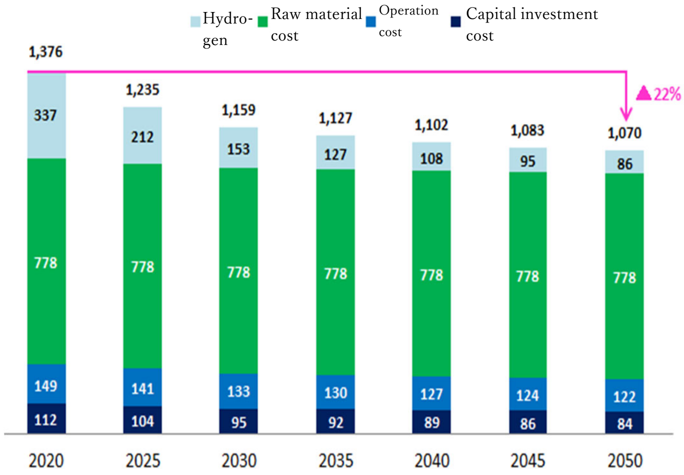
Figure 2-3 Map of the world's SAF supply status

3. Challenges for further expansion and the future outlook

The previous chapter summarized the characteristics, production technologies, and raw materials of SAF as well as the current status of supply and demand and their outlook. SAF is currently attracting attention and raising expectations as the key for decarbonizing the skies, but are there any challenges to overcome for expanding the use of SAF in the future? This chapter looks at the challenges faced by SAF and its future outlook.

The greatest challenge for increasing the use of SAF is to reduce production costs. **Figure 3-1** below shows the SAF production cost for each technology from 2020 toward 2050, revealing that **SAF is extremely expensive to produce as of 2020, costing roughly 3 to 7 times as much as jet fuel (estimated at $500/tonne)**. As for the feasibility of reducing costs going forward, HEFA, the most mature technology that has already been commercialized, is the most cost competitive and is expected to remain so. However, it is estimated that the cost of HEFA can be reduced by only 20% by 2050 due to the difficulty of drastically cutting its raw materials cost, which accounts for around 60% of the production cost (**Figure 3-2**). Meanwhile, Germany is focusing on power-to-liquid (e-fuel), which currently costs far more to produce than other technologies at $3,500/tonne. However, it is expected to be able to reduce that cost by around 67% by 2050 because of the sizeable scope for reducing renewable power generation costs and the medium- to long-term facility investment and operation costs (**Figure 3-1**).





Source: Prepared by the author based on World Economic Forum, Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation (November 2020)

Figure 3-1 SAF production cost: current status and outlook **Figure 3-2 SAF production cost: Breakdown (for HEFA)**

Are there any challenges concerning securing raw materials? The World Economic Forum estimates that approximately 500 million tonnes of SAF can be produced and supplied based on the potential of raw materials such as advanced feedstock and waste that does not compete with food. This is equivalent to 120% of the aviation fuel demand of 400 million tonnes as of 2030[16]. As for the supply volume, SAF raw materials such as biomass, residue, and municipal waste can also be used to produce heat energy by burning directly. They are also used for producing biomass power and waste incineration power and therefore compete as a primary energy source. Thus, the amount of raw materials for SAF production that can be secured may not be as large as the theoretical potential. It is also possible that the prices of raw materials could rise so much in the future that it would become difficult to purchase them. We can assume that projects that are already producing SAF on a commercial scale or are undergoing proof-of-concept can secure raw materials relatively easily. In the future, as the demand for SAF rises, the value of those raw materials may rise, or municipal waste, which is now available for free by bearing the collection cost, may be bought and sold in the future. As a potential increase in raw material costs would be passed directly onto the sales price of SAF, it could hamper the expansion of the fuel.

It is important to produce SAF in Japan also from the standpoint of curbing transportation costs (**Table 3-1** below). As there are no commercial SAF plants in the country as of now, Japan must depend on foreign imports for the time being. A tight supply-demand balance in the international market could not only push up the market price of SAF but also make it difficult to secure sufficient volumes.

---

[16] World Economic Forum (in collaboration with McKinsey & Company) (November 2020), *op. cit*., p.27

Table 3-1 List of domestic SAF manufacturers

Raw material		Technology	Company	Status
Oil	Waste cooking oil	HEFA-SPK	JGC Holdings, JGC Japan, REVO International, Cosmo Oil	NEDO PoC under way (till 2024)
	Microalgae	HC-HEFA	IHI	NEDO PoC done; supplied to domestic flights
	Euglena	HC-HEFA	Euglena	NEDO PoC under way (till 2024)
Biomass	Wood, pulp	FT-SPK	JERA, Mitsubishi Power Toyo Engineering, Itochu Corporation	NEDO PoC under way (till 2024)
		ATJ	Biomaterial in Tokyo Sanyu Plant Service	NEDO PoC under way (till 2024)
	Ethanol	ATJ	ANA, Mitsui Corporation (utilizing US LanzaJet's technology)	GI fund* being considered
Municipal waste Exhaust gas	Common waste	FT-SPK	JAL, Marubeni, ENEOS, JGC, and others (utilizing US Fulcrum BioEnergy's technology)	PoC under way
	Plastics			
	Exhaust gas	ATJ	N.A.	N.A.
Synthetic fuel	CO_2 + green H_2	CO_2 electrolysis	ANA, Toshiba ES, Toshiba, Idemitsu Kosan, TOYO Engineering, Japan CCS	Feasibility assessment
	CO_2 + H_2O	Co-electrolysis	Seikei University, ENEOS, Nagoya University, Yokohama National University, Idemitsu Kosan, AIST, Japan Petroleum Energy Center	NEDO PoC under way (till 2024)
	CO_2 + green H_2	Direct FT synthesis		

Source: Prepared by the author based on various sources including Japan Airlines[17], NEDO and other corporate press releases

It must be noted that whether SAF supplies can be increased still depends greatly on technological breakthroughs. As described earlier, while the current market is being driven by HEFA, the greatest cost reduction toward 2050 is expected to come from power-to-liquid (e-fuel). Power-to-liquid needs renewable and other clean electricity supplies, but currently, renewable electricity supplies are tightening as the world strives to achieve carbon neutrality. It will be necessary to secure large quantities of inexpensive clean electricity, but the fight for it is expected to intensify for various uses. Japan estimates that 23 million kl (18 million tonnes) of SAF will be introduced in 2050[18], but this deviates from the estimated total SAF production and supply from HEFA, gasification, FT synthesis, and ATJ by as much as 11 million kl (8 million tonnes) as of 2050. The gap is planned to be closed by producing SAF from algae[19]. The production of biofuels from algae dates back as far as the 1970s when Japan experienced two energy crises. Ventures mushroomed mainly in the United States around 2010 when oil prices soared, but most of them withdrew after they failed to achieve mass production. Therefore, technological breakthroughs are still needed to produce large quantities of biofuels from algae. If domestic SAF production does not proceed smoothly, Japan will have to continue to depend on imports and bear high transportation costs. Investing in a broad range of technologies is essential for enhancing energy security as well.

---

[17] Japan Airlines (February 17, 2022), "*The Role Domestic SAF Will Play*", https://www.jttri.or.jp/seminar220217-05.pdf

[18] Japan Airlines (October 8, 2021, press release), ANA and Japan Airlines Towards 2050 Carbon Neutral Joint Report on SAF, https://press.jal.co.jp/ja/release/202110/006263.html

[19] Japan Transport and Tourism Research Institute (February 17, 2022), "*Challenges and Solutions for the Overall Supply Chain Towards the Expanded Use of SAF in Japan (report)*", https://www.jttri.or.jp/seminar220217-06.pdf

As described earlier, various efforts are currently under way in Japan utilizing mainly government aid, including R&D funds from NEDO, which aims to establish a domestic SAF production system early on and to reduce costs. However, with no SAF production project yet commercialized, it is difficult to reduce production costs significantly in the near term. As such, in addition to government aid, it will be necessary to simultaneously consider a mechanism for society as a whole to absorb any rise in costs resulting from using SAF. As an example, European airlines such as Air France and KLM have a system whereby any SAF-induced increase in fuel cost is added on to the ticket price as a biofuel surcharge[20]. Further, more and more companies are voluntarily paying for the cost of offsetting the GHG emissions arising from their employees' international business air travel[21]. To expand the use of SAF going forward, it will be necessary to consider similar private-sector efforts that promote behavioral changes.

Conclusion

Recently, SAF has attracted steadily increasing attention. SAF production and supply projects led by the private sector are already being implemented in various places, but so far, the global supply of SAF is still small and it costs several times more than jet fuel. Further, as the raw materials used for SAF production must be absolutely sustainable, there is a risk that raw materials costs may rise in the medium to long term and pose a challenge. On the other hand, looking at the situation as a whole, SAF is likely to play an important role in the medium to long term in the international aviation sector, in which valid options for decarbonization are limited. To reduce costs sufficiently for the expansion of SAF going forward, technological breakthroughs by leveraging policy measures as well as a mechanism for sharing the costs by society as a whole are needed.

Contact: report@tky.ieej.or.jp

---

[20] France24 (January 10, 2022), "Air France-KLM adds biofuel surcharge to plane tickets," https://www.france24.com/en/live-news/20220110-air-france-klm-adds-biofuel-surcharge-to-plane-tickets

[21] BCG's Net-Zero Strategy, https://www.bcg.com/about/net-zero