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Sustainable Aviation Fuel

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Contents

Executive Summary

The aviation sector is currently, and will likely proportionally grow, as a significant contributor to global emissions. Sustainable Aviation Fuel (SAF) is widely acknowledged as being the most suitable method for short- to medium- term decarbonisation and there will likely be significant demand for SAF in the next two decades, at a minimum. Several differing SAF production processes are now approved, utilising a range of feedstocks. Of varying commercial availability and authorised blend-rates, the commercial success of each process is so far unclear. Production facilities are rapidly being developed, often due to expanding regulation and backed by offtake agreements from airlines, or with the real/promised delivery of grants and subsidies by governments.

In Europe, projected demand until 2027-2030 should be met by currently announced capacities, whereas in the US, incentives favouring production of renewable diesel will likely inhibit SAF demand being realised. Assessing the sustainability of SAF is complex, depending heavily on the production context. Theoretically, emissions savings of 94% relative to petroleum-derived jet fuel should be achievable. 35% savings with real-world conditions have been proven, and it is likely the total environmental impact savings will fall somewhere in the 30-60% range. Feedstock security and Indirect Land Use Change must also be considered for their environmental and social implications. Any use of SAF is a reduced amount of additional carbon introduced into the global carbon cycle, whereas 100% of the emissions from fossil jet fuel is newly introduced. Given the required techno-economic developments required for alternative technologies, SAF offers a valuable way to reduce environmental impact if correctly utilised.

Introduction

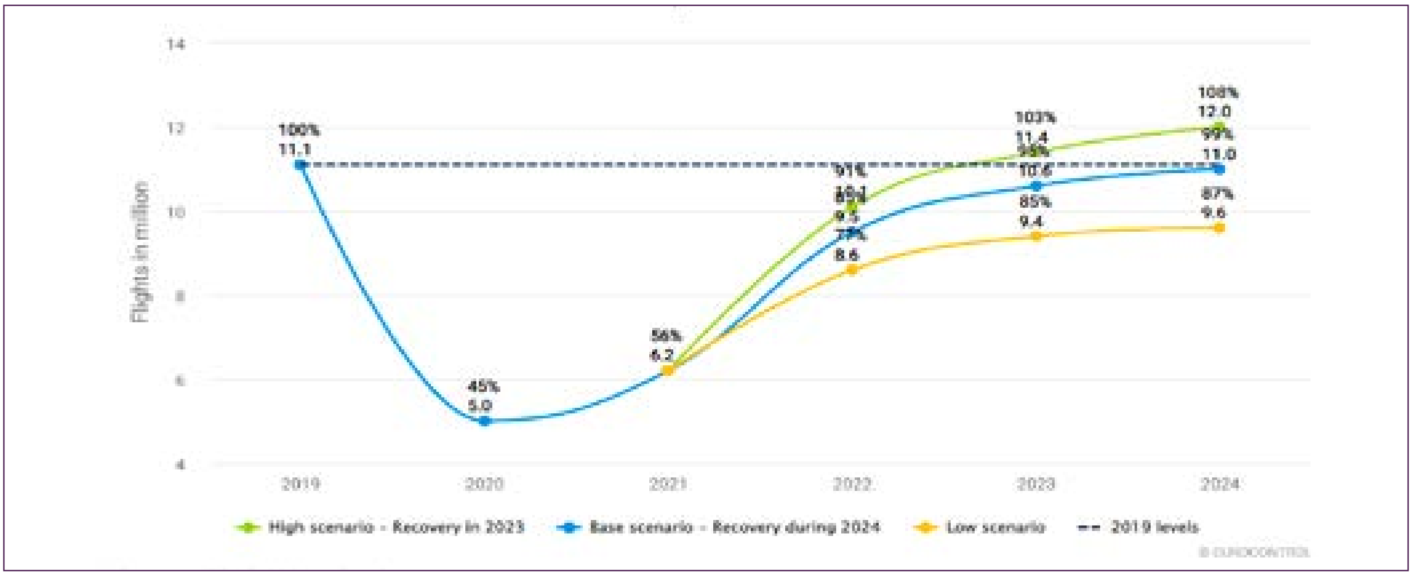
Every metric tonne[i] of petroleum-based jet fuel burned produces 3.16 tonnes of CO_2 in addition to other emissions such as nitrogen oxide, soot and other radiative-forcing mechanisms[1]. Research suggests that climate impacts of all propulsion related emissions could be two to four times larger than those of CO_2 emissions alone[2]. Emissions from the aviation industry were 1.1 gigatons (Gt) in 2019, with this figure is set to double to 2.1gt in 2050[3]. There will be significant demand for Sustainable Aviation Fuel (SAF) in the next two decades at a minimum, and likely beyond. Commercial opportunities exist with a variety of technologies being employed. However, it is still nascent industry, therefore data on size and growth is hard to find. Moreover, the genuine sustainability of the technology can be brought into question. Aiming to provide an overview of SAF and its production, this research paper has been written using academic and financial institutions research, as well as NGO, company reports and white papers. After providing an overview of the argument for the use of SAF, the paper outlines the demand and supply forecasts and delves into the sustainability credentials.

[i] 1 Metric tonne (mt) is equal to 331 US gallons.

Background: Decarbonising the aviation sector

Despite the Covid-19 pandemic, the war in Ukraine and global economic slowdown, the aviation sector is back on a steep recovery trajectory. Globally, passenger numbers are expected to grow from around 3.2 billion in 2022[4] to 5.6 billion by 2030[5]. In Europe, there are expected to be 9.5 million flights this year, 85% of 2019 levels. By 2024 this is expected to return to 11 million flights per year, matching 2019 levels. Boeing predict that the world's fleet of commercial planes will have doubled from 24,500 by 2042[6]. Aviation accounts for about one billion metric tons or about 3% of global CO_2 emissions annually[7].

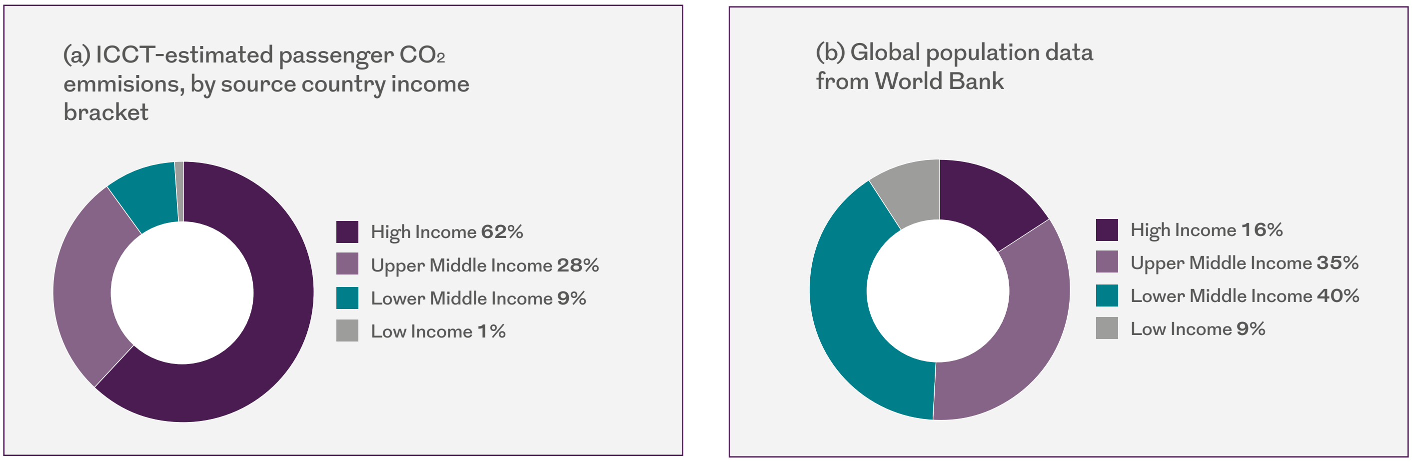
Figure 1: 3-year forecast for European[i] flights 2022-2024



[i] Europe = The European Civil Aviation Conference (ECAC) 44 member states.
Source: Eurocontrol (2022)[8]

Whereas currently less developed countries (which contain nearly half the world's population) account for only 10% of all passenger transport-related aviation CO_2, this will shift and become the main driver of growth, as increased development and higher disposable incomes allow for access to aviation. India and China are expected to see their emissions from aviation rise by 421% and 169% respectively[9]. By 2050, the UN's ICAO (International Civil Aviation Organisation), the specialised agency in charge of sector administration and governance, have estimated that aviation emissions will roughly triple by 2050, at which time aircraft may account for 25% of the global carbon budget[10]. It is therefore critical to decarbonise this sector.

Figure 2: CO_2 emissions from passenger aviation operations and total population in 2018, by country income bracket (United Nations, 2019; World Bank, 2019)



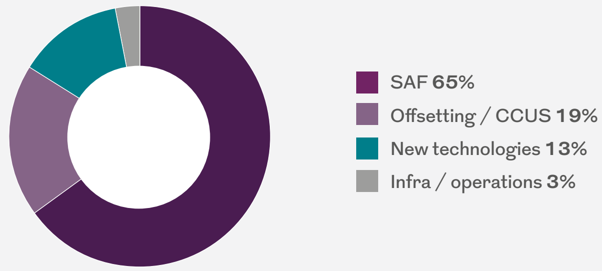
Source: International Council on Clean Transportation (ICCT)[10]

The sector is considered hard-to-abate[11]. The sector's average carbon abatement cost, for example, is more than five times higher than those in power generation or agriculture[12]. Several marginal operational and technological decarbonisation avenues are constantly being pursued. Optimisation of flight routes, airframe improvements and increases of jet engine energy efficiency have resulted in today's aircraft being 85% more efficient than 1960s jets and 20% more efficient than the jets they are replacing[13]. Nonetheless, such reductions are insufficient to counterbalance expected growth.

More material decarbonisation pathways such as electric- or hydrogen- powered aircraft have serious long-term potential; however, these are not expected to enter the market for the next decade at least due to significant technological limitations. For example, at a given mass, jet fuel provides 60 times more energy than current battery technologies[14], and even Airbus, who conceivably might be more optimistic than most, concede that their ambition is to bring a 'zero-emission' commercial aircraft by 2035 at the earliest[15]. Additionally, aircraft replacement cycles of 15-20 years mean that aircraft entering service now will still be in operation in 2040, slowing the mainstreaming of either technology.

In contrast, Sustainable Aviation Fuel (SAF) a so-called 'drop-in' fuel, can be readily used with existing infrastructure and aeroplanes and is therefore seen as the most achievable and effective pathway to reduce emissions in the immediate future[16]. In 2021, IATA (International Air Transport Organisation) member airlines articulated a commitment to achieving net zero emissions by 2050, using the methods shown in Figure 3.

Figure 3: IATA proposed method for achieving net zero carbon emissions by 2050



*** CCUS - Carbon Capture Utilisation and Storage
Source: RBC Capital Markets, 2023[17]

Sustainable Aviation Fuel (SAF)

SAF is a substitute for fossil fuel derived jet fuel. Produced from a variety of feedstocks (including waste oils, fats, agriculture and forestry residue, wood, carbon dioxide, and water), different competing processes exist to turn the raw ingredients into kerosene like fuel with the high energy density specifications required. Seven processes currently exist, with four of the most common ASTM (American Society for Testing Materials) certified shown in Table 1. The blend rate (i.e., the balance between SAF and regular fuel) can vary between processes. Currently the maximum rate permissible under ASTM-approved SAF production pathways is 50%, ensuring the resulting product still meets the Jet A/A-1 specifications and can therefore safely be used in commercial aviation without further adjustments. This is because current tolerances within traditional jet fuel for impurities (aromatics and heteroatomic compounds) are accounted for in the existing engineering of components (for example, rubber seals expand in the presence of sulphur). However, these compounds are not present in SAF, meaning that components need testing in their absence[18]. Feasibility studies are being undertaken by plane manufacturers with the aim for unblended (100%) SAF certification by 2030[19].

Table 1: Four of the most common ASTM-approved SAF production processes

Production type	Feedstocks	Current maximum blend (%)	Approval year
Hydro-processed Esters and Fatty Acids (HEFA)	Waste fats, oils, greases and other lipids	50%	2011
Fischer-Tropsch (FT)	Municipal solid waste and carbon capture	50%	2009
Alcohol-to-Jet (ATJ)	Sugar and starch crops	50%	2016
Hydro-processed Fermented Sugars (HFS)	Sugar	10%	2014

Source: J.P. Morgan (2022)[20]

Brief overview of different processes

Hydro-processed Esters and Fatty Acids (HEFA) is considered a mature technology which is safe, proven and scalable[21], and is also the only commercially available process currently. Due to its similarity with conventional oil refining in both process and technology, the use of the technology to create renewable diesel (RD), and the possibility for conventional refineries to be converted, it has the lowest cost of production[22]. The RD industry is more established than that for SAF, especially in the US, where consumption of RD totalled 1.3bn gallons in 2021 versus 5mn for SAF[23]. Whilst low in technology risk, HEFA generally has higher feedstock risk. The feedstocks used can compete with food supplies and analysts have suggested that forecast change of demand of HEFA projects in the US will lead to material inflation of feedstocks and may result in the cancelation of several HEFA projects[24].

Fischer-Tropsch (FT) and Alcohol-to-Jet (ATJ) generally have lower feedstock risks, but face techno-economic uncertainty due to only existing at commercial 'pilot' level and not being produced at high levels. The feedstocks for these pathways require high-temperature deconstruction and/or biological catalysts/chemicals to create intermediaries leading to higher build costs. However, due to being waste the feedstocks generally have a lower cost and are also more policy compliant[25].

Power-to-liquid (PTL) is a form of FT which can be used to create a non-biomass based (i.e., synthetic) SAF; however, proof of concept is not expected until after 2025[26]. Renewable energy is used to power electrolysers which produce green hydrogen. Carbon feedstocks are then synthesised with the green hydrogen to generate liquid hydrocarbons. PTL fuels exhibit the most uncertainty today and production costs are very high, likely necessitating the presence of significant government subsidies[27]. The carbon used in the process can be sourced from three options: industrial waste gas and sustainable biomass (BECCS) which both use point source capture, or direct air capture (DAC). Research suggests that a market ramp-up in 2030 could solely be supplied by CO_2 from point source capture, but for large scale introduction until 2050 varying amounts of CO_2 from DAC would be needed[28]. A second hurdle relates to the supply of renewable electricity or green hydrogen which requires more sustainable electricity than currently available at localised levels.

Hydro-processed Fermented Sugars (HFS) has high feedstock costs and policy risks due to competing with food using sugar crops, and plants are expected to have high operating costs due to the process of producing sugar from biomass[29]. Added to this, the maximum blend rate of 10% is likely to limit potential demand.

Expanding regulation

SAF is likely to remain significantly more expensive than fossil fuels for decades, therefore government policy support (alongside scientific advances) will be needed. Current and prospective policies suggest that SAF adoption is likely to accelerate in 2025 and again in 2030. At a multinational level, CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) has been passed by the UN's ICAO (International Civil Aviation Organization), the specialised agency in charge of sector administration and governance. Under the scheme, airlines will be required to monitor emissions on all flights and offset growth above the 2019 baseline in emissions from flights between participating states by purchasing and cancelling eligible emission units generated by projects that reduce emissions in other sectors[30]. The programme is voluntary at a country level through 2026. Starting in 2030, emissions reduction mandates shift towards individual airlines. CORSIA is broken into three phases running from 2021 to 2035. SAF's purported emissions savings would reduce the number of offsets required, thus even though CORSIA does not directly call for its use, demand should increase.

Table 2: Select proposed and enacted regulation

Region	Country/ region	Actions being taken	Mandatory blend rates milestones	Stage of implementation of legislation	Other comments
Europe	EU	REfuelEU Aviation Initiative	2025: 2% 2030: 6% 2035: 20% 2040: 34% 2045: 42% 2050: 70%	Legislation was voted for by parliament in Q3 2023 and once approved by council will apply from Jan 2024.	Also features additional blending requirements for synthetic fuels[31].
	UK	Sustainable Aviation Fuels Mandate	2030: 10%	Consultation held and outcomes decided	'Jet Zero strategy' consultation, domestic aviation and airports net zero by 2040[32].
	Sweden	Greenhouse gas (GHG) reduction mandate (SFS 2021:412)	2022: 1.7% 2030: 27%	Enacted	Users that are taxable for gasoline must reduce the climate impact of their fuel by a certain percentage each year. In 05/23 the newly elected Sweden Democrats pared back the requirements[33].
North America	US	Federal Aviation Administration (FAA) Aviation Climate Action Plan (ACAP) SAF Grand Challenge (SAFGC) Sustainable Skies Act (SSA)	FAA ACAP = net zero by 2050 SAFGC = 3bn gallons produced by 2030, 35bn by 2050	SSA introduced to Congress	SSA would mandate US$2/gallon tax credit for producers until 2031[34, 35, 36, 37].
Asia	China	14th five year plan (FYP)	-	Enacted	China has announced a plan for peak carbon emissions in 2030 but are yet to publish SAF targets[38].
Australasia	New Zealand	Civil Aviation Bill 2021	-	Proposed	Amendment means that CORSIA would become legally binding[39].

Source: European Parliament (europa.eu)11-09-2023[31], Department for Transport (2022)[32], energimyndigheten.se[33], Federal Aviation Administration (2021) 2021 United States Aviation Climate Action Plan[34], J.P. Morgan (2022)[35], The White House 09-09-2021[36], Congress.gov (2021-2022)[37], Institute of Energy, Peking University (2022)[38], Office of the Associate Minister of Transport (2019)[39].

At EU level, the proposed ReFuelEU Aviation initiative (part of the 'Fit for 55' package) would mandate SAF blend rates of 2% in 2025, 6% in 2030, 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050[40]. The proposal includes a blending mandate imposed on aviation fuel suppliers, with the obligation for the suppliers to ensure that all aviation fuel supplied to aircraft operators at EU airports contains a minimum share of SAF, including a minimum blend of synthetic fuel (including 1.2% in 2030 and 35% in 2050). As an enforcement mechanism, airlines will be expected to pay at least the twice the annual average price of jet fuel for the missing SAF volume, while the penalty for suppliers is at least twice the difference between the annual average price of kerosene[41]. In addition to this, certain individual countries have also set more stringent blending targets, with Norway, Finland and Sweden setting a blending mandate of 30% by 2030[42].

France, Sweden and Norway already have active blending mandates in place varying from 0.5% to 1.7% per flight. The UK has adopted a blending mandate which could at its maximum target a 10% rate for 2030[43].

In the US, three policies are likely to impact SAF production[44]. The Federal Aviation Administration's (FAA) 2021 Aviation Climate Action Plan targets net zero emissions for the airline industry by 2050[45]. Although the current plan is high level, it targets reducing production costs through government incentives and expanding supply and end use of SAF through federal programmes.

The Sustainable Aviation Fuel Grand challenge announced in 2021 targets US SAF production of at least 3bn gallons by 2030 (or 13% of total jet fuel consumption in 2019) and enough SAF production to meet 100% of demand in 2050 (a projected 35bn gallons)[46]. It has also announced initial funding support for SAF capacity.

Finally, the Sustainable Skies Act currently proposed in Congress would institute a tax credit (of up to US$2 per gallon) for SAF producers[47], and federally the Inflation Reduction Act's SAF incentives provide a tax credit of US$1.25 to US$1.75 per gallon effective in 2023 and 2024[48].

Elsewhere around the world, including in Asia-Pacific, the policy approach appears to be more wait-and-see[49]. In China, plans are in the early stages and they do not yet have concrete targets for SAF; however, given predictions that by 2041 intra-China will be the largest aviation market[50], any regulation would likely be material to the SAF market. New Zealand have introduced the Civil Aviation Bill in 2021 which proposes to make it a legal mandate for airlines' commitments to CORSIA[51]. Given CORSIA's voluntary nature, this policy could serve as a model for other countries to further require compliance by participating countries.

SAF demand outlook

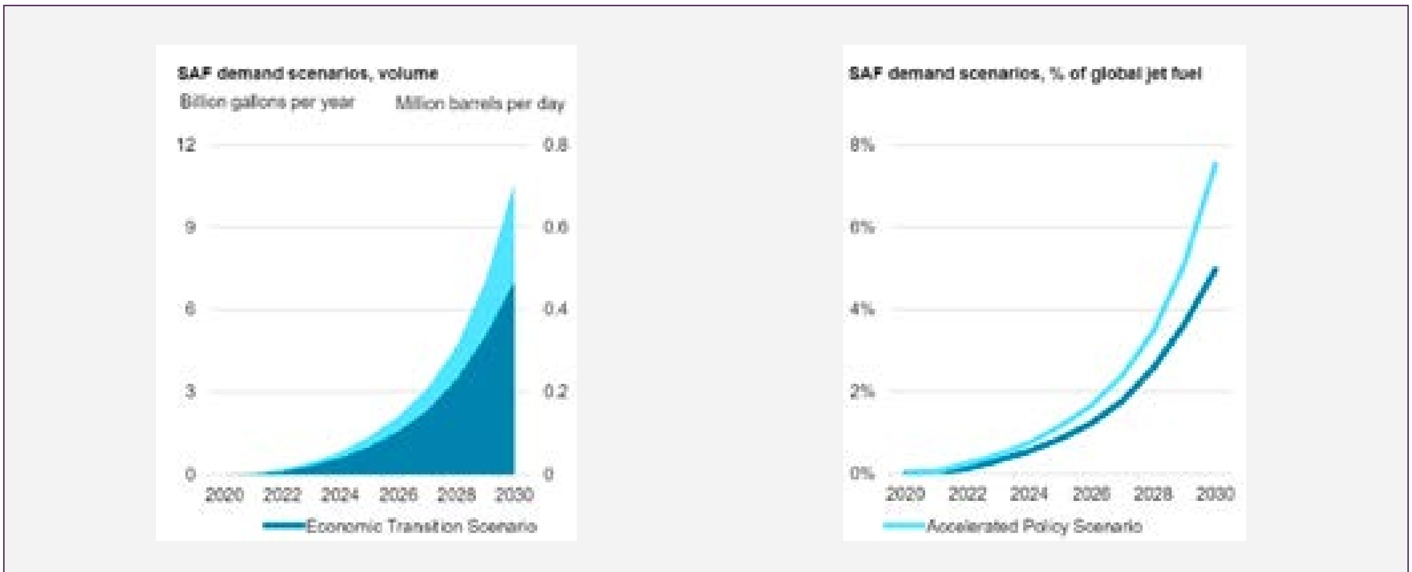
Estimates suggest currently SAF represents 0.1% of the total jet fuel consumption, or around 70mn gallons[52]. JP Morgan analysts suggest that SAF will have minimal impact on jet fuel supply/demand balances through 2025, and the ramp-up will be in the latter part of this decade. They estimate potential demand in 2030 of 4.5bn gallons (3bn in the US, 800mn in the EU, 700mn in Asia)[53], while BloombergNEF (BNEF) forecast this will be closer to 7bn gallons[54] and RBC Capital Markets closer to 8bn[55], roughly 5% of total jet fuel demand.

Likely in response to CORSIA and consumer expectations[56], nearly 30 airlines have published SAF commitments (and 38 have published net zero targets)[57]. As a result, offtake agreements (where airlines commit to purchasing quantities of SAF at a future date) are becoming commonplace (e.g., between Lufthansa and Shell[58]), with other airlines choosing to invest or partner with suppliers (e.g., British Airways and LanzaJet partnering to explore construction of a commercial SAF plant in the UK[59]). Additionally, some airlines have set their own voluntary mandates (e.g., KLM announced in January 2022 that they will be adding 0.5% SAF to all flights departing their hub, Amsterdam[60]). RBC Capital Markets estimate that currently announced airline demand is far below policy targets, suggesting more offtake agreements will be signed[61].

Similarly, cargo airlines have made bold commitments to SAF as they have sought to match each other's climate commitments. FedEx, the world's largest air freight provider, and DHL have both introduced blending targets of 30% for 2030[62]. UPS have a 30% blending target for 2035[63]. Given that these companies' fleets rival many passenger airlines, these commitments are significant.

Stifel Nicolaus analysts are quick to point out that they view voluntary SAF targets as aspirational, and they require reinforcement by regulation[64]. The BNEF forecasts in Figure 4 show two global demand scenarios[65]: the economic transition scenario which includes only existing policies, excluding those proposed or under consideration, and an accelerated policy scenario which includes the additional policy mechanisms or targets being developed and under consideration. Both these scenarios can be considered somewhat conservative given that further countries may announce policies going forward.

Figure 4: Global demand scenarios



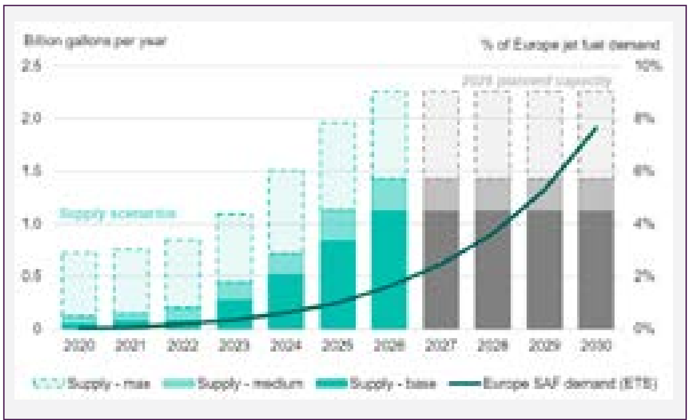
Source: BloombergNEF (BNEF) 2022[66]

SAF supply outlook

With the arrival of newly created products, supply should follow demand. BNEF analysts suggest current worldwide capacity is around 200mn gallons, whilst JP Morgan analysts' estimates are much lower at just 70mn gallons (5mn in North America, 65mn Rest of World). By 2026, BNEF predicts global capacity to be at 2.6bn gallons, around 2% of aviation fuel demand. For Europe, various analyses suggest demand should be achievable with current announced capacities until between 2027-2030[67, 68, 69]. A contrasting opinion from RBC Capital Markets is that 2030 supply (6bn-19bn gallons) is potentially well above current demand[70].

BNEF estimates in Figure 5 that Europe is on track to meet demand, with potentially even spare capacity in the short term. Table 3 on page 12, shows how besides the US, most other companies are based in Europe. Yet by 2030 new capacity will be needed to meet demand.

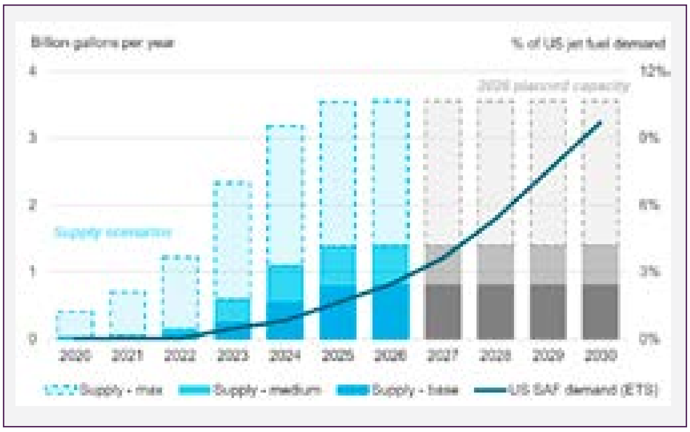
Figure 5: Europe demand and supply. Demand based on economic transition scenario (ETS)



Source: BloombergNEF (BNEF) 2022[71]

The US is the world's largest producer of SAF. Whilst JP Morgan estimates a 2025 capacity exceeding 5.5bn gallons[72], BNEF suggests even at its top range this will likely max out at 3.5 billion gallons. The US also has by far the largest pipeline of renewable fuel projects, but the vast majority are destined for renewable diesel (RD), rather than SAF, hence the reason for the large variation between medium and maximum supply shown in Figure 6 (and RBC Capital markets 2030 supply estimate[73]). The favourable economic incentives, which currently favour RD, will have to change if the US is to meet its 3bn gallon target by 2030. To meet this, rapid feedstock and technology and diversification is required[74].

Figure 6: US demand and supply. Demand based on economic transition scenario

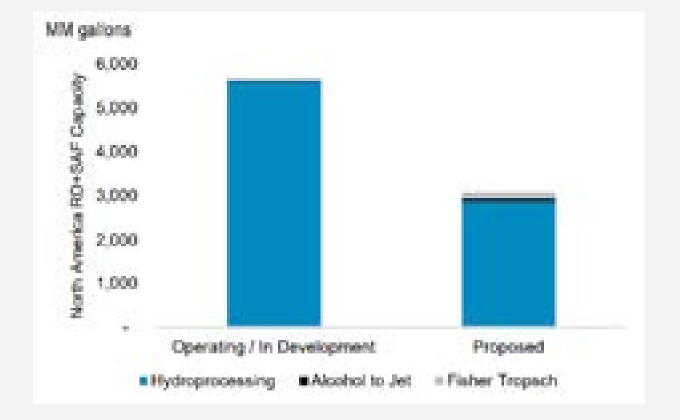


Source: BloombergNEF (BNEF) 2022[75]

Despite growing interest and targets, SAF supply remains scarce and highly concentrated among a few producers. HEFA is the only production method commercially available currently and will be essential in the near term until other technologies become commercially available. A supply challenge relating to HEFA is that the majority of current capacity is earmarked for RD projects, rather than SAF.

This is especially true in the US, although the technology gives producers the flexibility to shift production to SAF. However, the largest challenge for scaling up HEFA production is the feedstock pool. Today, the world has enough waste and residue lipids to produce roughly 20mn tonnes of SAF, equating to about 5% of estimated 2030 jet fuel demand. While a significant share of this feedstock is already used in industry and other fuel applications, feedstock is scattered widely and difficult to collect in full without a complex infrastructure, resulting in significant unused reserves[76]. RBC Capital Markets estimate that around 25% of contracted supply is at risk of delay given complexities in production and gaining access to feedstocks[77].

Figure 7: Dominance of hydro processing production method (North America)



Source: J.P. Morgan (2022)[78]

Production using FT and AtJ processes are forecast to be producing by the end of 2023. JP Morgan estimate current worldwide capacity is just 70mn gallons (5mn in North America, 65mn Rest of World). In 2023 this is estimated to grow to 518mn gallons (145mn in North America, and 373mn Rest of World) and capacity plans are said not to present a meaningful constraint on SAF consumption. Forecast production is currently concentrated in the US, with North American RD and SAF capacity possibly to exceed 5.5bn gallons by 2025. For the rest of the world, this figure is forecast to be around 3.9bn by 2025. Here producers are predominantly located in Europe, with a few outliers in Singapore and China[79].

If sufficient incentives exist and production of fuels is optimised for SAF, advanced and waste feedstocks could supply 490mn tonnes of SAF every year, more than the total projected fuel demand for 2030[80]. The US will not currently be able to meet its 3bn gallon target, and rapid feedstock and technology diversification will be required. A significant pipeline of renewable diesel projects in the US will prohibit new SAF announcements from accessing fats, oil and grease (FOG) feedstocks.

Sustainability credentials

The level of CO_2 and other pollutants emitted from a jet engine is largely equivalent between SAF and fossil-based jet fuel. However, the net climate effect is significantly reduced as a result of more accurate and holistic accounting of emissions associated with the fuel, including its production methods and feedstock source. Whereas all carbon from fossil fuels is newly introduced to the global carbon cycle due to its extractive origin, SAF carbon sources are already present in or would otherwise release back into the atmosphere as they degrade. Therefore, SAF reduces the amount of additional carbon introduced. Besides, CO_2 emissions, it is also important to consider food security and Indirect Land Use Change (ILUC). No single sustainable feedstock will answer every need; the industry will need to consider and adopt a range of options. Other pollutants associated with aviation, such as noise pollution (which can negatively impact humans[81] and animals[82]), are not mitigated through the use of SAF.

Figure 8: Sustainability credentials of different feedstocks

All feedstock must fulfil sustainability criteria

Feedstock type	Feedstock category			Feedstock[vi]	Sustantial GHG savings potential[vii]	No fundamental sustainability concerns[viii]
1st gen / crop-based	Edible oil crops			Palm	X	X
1st gen / crop-based	Edible oil crops			Soybean	X	X
1st gen / crop-based	Edible oil crops			Other (inc. sunflower)	X	X
1st gen / crop-based	Edible sugars			Sugar cane	(✓)	X
1st gen / crop-based	Edible sugars			Maize	X	X
1st gen / crop-based	Edible sugars			Other	X	X
Advanced and waste	Waste and residue lipids[ii]			Used cooking oil (industrial or private sources)	✓	✓
Advanced and waste	Waste and residue lipids[ii]			Animal waste fat (tallow)	✓	(✓)
Advanced and waste	Waste and residue lipids[ii]			Other (incl. tail oil, technical corn oil, fish oil, palm oil mill effluent, palm fatty acid distillate	✓	(✓)
Advanced and waste	Purposely grown energy plants	Oil trees on degraded land		Jatropha, pongamia	✓	(✓)
Advanced and waste	Purposely grown energy plants	Rotational cover crips	Oil cover crops	Camelina, carinata, pennycress	✓	(✓)
Advanced and waste	Purposely grown energy plants	Rotational cover crips	Cellulosic cover crops	Miscanthus, switchgrass, reed cannarygrass	✓	(✓)
Advanced and waste	Agricultural residues			Rice straw	✓	✓
Advanced and waste	Agricultural residues			Sugar cane begasse	✓	✓
Advanced and waste	Agricultural residues			other (inc. corn stover, cereal residues)	✓	✓
Advanced and waste	Forestry residues[iii]				✓	✓
Advanced and waste	Wood-processing waste[iv]				✓	✓
Advanced and waste	Municipal solid waste[iv]				✓	✓
Recycled carbon	Reusable plastic waste				X	✓
Recycled carbon – Non-biomass based[i]	Idustrial waste gas			CO_2 from point source capture (CCS)	✓	✓
Recycled carbon – Non-biomass based[i]	Idustrial waste gas			Other (e.g flue gas from steel production)	✓	✓
Recycled carbon – Non-biomass based[i]	CO_2 from direct air capture (DAC)				✓	✓

Focus of analysis ✓ Satisfied (✓) Potentially satisfied[ix] X Not satisfied

i. Adjustment of RED II category "Renewable fuel of non-biological origin"; ii. Some not included in RED II definition of advanced (e.g., used cooking oil, animal waste fat), while others are (e.g., tall oil, POME); iii. Left overs from logging operations, including leaves, lops, tops, damaged or unwanted stem wood; iv. By-products and co-products of industrial wood-processing operations, including sawmill slabs, saw dust, wood chip; v. May contain up to 20% non-reusable plastics; typically inefficient to separate organics and plastic; vi. Algae not assessed due to limited feasibility; vii. In line with RSB: >60% based on LCA,; viii. Mainly related to food security and land use change; ix. Depending on local circumstances

Source: WEF & MCKinsey 2020[83]

Output of CO_2 and other pollutants

Theoretically, should power-to-liquid (PTL) become feasible using renewable electricity and carbon from sustainable biomass or DAC, then it should be possible to eliminate nearly all CO_2 emissions from fuel combustion. However, PTL is not yet techno-economic feasible. Whereas airlines frequently claim CO_2 emissions savings between 70-80+% versus conventional kerosene[84, 85], research indicates such percentages are mostly theoretical, and therefore may not present real-world savings.

Only a limited number of Life Cycle Assessments (LCA) of SAF have been conducted (see Appendix 1); theory suggests potential emissions savings of up to 94% (or more than 100% when considering negative greenhouse gas (GHG) emissions of ILUC contribution for some pathways)[86]. A study integrating the current complexities of production and other real-world variables shows that savings of 35% are feasible[87].

Elsewhere, it is suggested that with a fully decarbonised supply chain and once CO_2, nitrogen oxide, water vapours and contrails have been taken into account, total environmental impact savings of 30%-60% are more realistic[88]. It is sensible to assume the true efficiency will not be known until further LCAs are carried out of differing scenarios.

In addition to the CO_2 emissions produced from burning fuels, the emitting of nitrogen oxides, soot, and water vapor, among other effects, create contrails and cirrus clouds that cause radiation and affect the climate. The CO_2 emitted from kerosene burned in flight can stay in the upper atmosphere for 50 to 100 years, and nitrogen oxide for several weeks, affecting the ozone layer. As such, the total aviation effects may be approximately 2 to 4x higher than the pure CO_2 effects would indicate[89].

Food security and Indirect Land Use Change (ILUC)

A material factor requiring consideration when looking at the sustainability of fuels derived from biogenic feedstocks is food security and land use change. Environmental integrity is key to selecting suitable feedstock, and Figure 8 on page 11, gives some indication of how different feedstocks compare. This is important from both a social and environmental perspective. For the former, increased demand and purchasing power of SAF producers might divert edible crops away from local populations who require it for sustenance. For the latter point, edible oils and sugars result in more CO_2 than waste and residues-based fuels, and in some cases can even produce more CO_2 than fossil jet fuel. To disincentivise unsustainable intensive farming of crops for the sole purpose of SAF, the EU's mandate says fuels made from food and feed crops will not count toward SAF targets[90].

ILUC is a commonly cited issue of biofuels and refers to the change in land use outside a biomass production area that is induced by changing the use or production quantity of a feedstock that was produced in that area. Thus, crops previously produced in the biomass production area are being produced elsewhere to meet demand, resulting in some land being converted to agricultural land[91]. ILUC considers impacts from economy-wide market mediated responses, for example, reallocation of land resources across uses, price induced improvements in crop yields, crop intensification, shift in trade patterns of food and agricultural products as well as substitution between food crops and SAF's coproducts[92]. The effect of the above mean that even if producing biomass feedstocks for SAF on low carbon soil or idle croplands which can increase carbon sequestration[93], the impact may still be polluting. Aside from pollution and potential negative impacts on biodiversity, this may also lead to displacement of workers and Indigenous Peoples, as well as cultural disruption.

Due to its similarity with conventional oil refining in both process and technology, HEFA generally has low technology risk, but high feedstock risk. The feedstocks used are typically waste fats, oil, and greases (FOGs) and vegetable oils, which can compete with food supplies and often do not screen as favourably on sustainability metrics due to indirect land-use concerns. Nonetheless, a recent study suggested that 15 of the assessed pathways have lower full life-cycle emission intensity than kerosene[94].

Relevant companies

The following list contains solely those companies that according to our research already do or have explicit plans to develop SAF, rather than those which develop RD. A majority are private.

Table 3: Select SAF producers

Company	Ticker	Company location
Aemetis	AMTX	US
Air Company	-	US
Alder Fuels	-	US
Alfanar	-	Saudi Arabia
Atmosfair	-	Germany
BP	BP	UK
Byogy Renewables	-	US
DG Fuels	-	US
Dimensional Energy	-	US
Enerkem	NRKM	Canada
Eni	ENI	Italy
Euglena Co	-	Japan
Fulcrum Bioenergy	-	US
Fidelis New Energy	-	US
Gevo	GEVO	US
Raven SR	-	US
Red Rock Biofuels	-	US
Repsol	REP	Spain
Oriental Energy	-	China
LanzaTech Global	LNZA	US
Neste	NESTE	Finland
Norsk e-Fuel	-	Norway
OMV	OMV	Austria
Philips 66	PSX	US
SG Preston	-	US
Shell	SHEL	UK
SKYNRG	-	Netherlands
Synkero	-	Netherlands
TotalEnergies	TTE	France
Velocys	VLS	UK
WasteFuel	-	US
World Energy	-	US

Source: Royal London Asset Management, October 2023. This does not constitute an investment recommendation. For information purposes only.

Criticisms

One of the major challenges in scaling up SAF is obtaining enough sustainable feedstock. The market is complex, with many feedstock types, geographical fragmentation and some disagreement on which resources are ethical, sustainable and compatible with production technologies. Additionally, in the medium to long term, SAF production should not be used to slowdown the introduction of technologies not reliant on fossil fuels.

Unlike reusable plastic, point-source-captured CO_2 from factory tailpipes and other industrial waste gas may have positive lifecycle savings but raise other concerns. From a broader sustainability perspective, SAF production should not create a business case for other industries to produce carbon waste and double counting must be avoided. If tailpipe emissions are captured and used for SAF, only the industrial site or SAF producer should get credit from the recycled carbon. Recycled carbons (excluding reusable plastics) could serve as bridging feedstocks however, helping scale and mature technology until more sustainable alternatives (e.g., CCS[95]) are available at lower costs.

Another challenge already highlighted is the risk that SAF presents opportunities for greenwashing. Intentional or not, this has already been seen from many airlines. Besides the obvious environmental critique of this, it may also lead to legal cases against parties involved, such as in the recent case brought by environmental groups against KLM[96].

Elsewhere, criticism has also come from airlines. Lufthansa points to the fact that the introduction of a quota at the European or German level would not only increase fuel costs for the company, but could lead to "distortion of competition, as competitors could circumvent this by 'tankering', i.e. carrying fuel on outward flights in excess of their requirements, or by operating multi-sector flights" (Lufthansa, Annual Report 2020)[97]. Regulators are seemingly aware of this problem; the UK's 'Jet Zero review' says details on a control mechanism will be published in due course[98].

Finally, government policies have faced critique. In a blog for the International Council on Clean Transportation (ICCT), their aviation and marine program director Dan Rutherford argues that the EU is implementing a comprehensive suite of policies to accelerate SAF markets with a "Polluter Pays Principle"[99]. In contrast, the author argues that the US is considering a short-term subsidy for airlines that may do little to unlock new long-term supply but rather just shuffle feedstocks from the road sector to aviation, with little net benefit. Similarly, SKYNRG have highlighted that the RFS, which makes up for most of the financial incentive in the US, currently only allows the use of biogenic feedstocks[100]. This means that for any production of SAF to qualify for participating in the RFS program, the feedstocks must come from biogenic sources such as vegetable and waste oils, cellulosic residues or corn. This contrasts with European SAF mandates, where food/feed crops are not eligible due to concerns of indirect land-use change effects and associated negative GHG impacts. This also means that the RFS currently does not incentivise renewable fuels of non-biological origin like PTL, despite the US' abundant and cheap renewable power resources. This creates a misalignment of policy and coordination of the SAF industry due to different policy metrics and guidelines for the sector in the US versus the EU.

Industry challenges

Developing the production pathways also requires confidence that SAF is the right solution, and government signals are important here. In the US, the proposed Sustainable Skies Act will play an important role, and in the UK, the Government recently announced a £165mn Advanced Fuels Fund with the aim being for the UK to have at least five commercial SAF plants under construction by 2025[101]. In the EU, the European Parliament have also supported the creation of a Sustainable Aviation Fund from 2023 to 2050[102]. Whereas offtake agreements signed with airlines may have been viewed with a degree of suspicion, government support is seen as a vote of confidence by investors[103]. There have also been calls for governments to create contracts for differences (CFD), agreeing a set price for the fuel underwritten by government, like those used for nuclear and offshore wind projects[104].

These announcements highlight the strong commitment from governments for the development of SAF both locally and for export and should encourage other members in the value chain (e.g., aircraft manufacturers, airports) to invest in infrastructure. According to the ICAO, 60 airports now have ongoing deliveries of SAF[105]. Most of these airports are clustered in the US and Europe, though major airports in other regions are beginning to follow. The high concentration of SAF in certain regions means international airlines will rely heavily on refuelling with SAF at those hubs in order to meet their targets[106].

Conclusion

Aviation is perhaps the hardest transport sector to decarbonise. With no clear commercially available solution to enable this, the industry will need to leverage several different tools to achieve its ambitious goal. Currently, most airlines, airports and producers agree that SAF is the most feasible solution to addressing aviation decarbonisation goals in the short term. SAF is only commercially viable with the introduction of blending mandates, government support, and/or rising carbon costs. Supply and demand dynamics will determine the success of each pathway. In a slow scale-up scenario, HEFA feedstock could be sufficient to power the industry until low-cost synthetic fuels become available at scale. In an accelerated scale-up scenario, demand requires all pathways to scale before all production technologies have matured and captured their full cost-reduction potential. Growth in China and other developing countries will be fundamental in determining the total output of the aviation sector, but there will likely be significant demand for SAF in the next two decades at a minimum.

Appendices

Appendix 1

There are a limited number of academic studies which conduct Life Cycle Assessments, an assessment process which aims to include the complete product life cycle from the production of the raw material to the final disposal of the product after the use phase (including all the pre-products and energy carriers used). Such analyses are inherently complex, consider an innumerable number of factors, and are theoretical in nature. As an example, this extract from Prussi et al.[107] demonstrates some of the aspects which need to be taken into account with the HEFA pathways:

> *For HEFA, oil extraction and jet fuel production lead to emissions associated with the required energy and chemical inputs: mainly electricity, natural gas, and hydrogen. Unlike the FT process, which relies on energy from the biomass feedstock, the HEFA process relies mainly on fossil-based inputs, leading to higher conversion emissions. If renewable electricity, natural gas and hydrogen are eventually used for these processes, their GHG emissions would be reduced significantly. There are two core LCA values for palm HEFA pathways because CH^4 (methane) emissions from the palm oil mill effluent (POME) can vary significantly depending on biogas recovery (CH^4 capture).*

Additionally, the assessments of SAFs have only recently been carried out. Whilst theory suggest potential GHG emissions savings of up to 94% (and more than 100% when considering negative GHG emissions of ILUC contribution for some pathways)[108], this assumes 1:1 substitution of traditional fuels. Another study looking more closely at current real-world conditions suggests a 'multi-blend' of fuels (32% HEFA, 6% ATJ, and 62% Jet A-1) can produce emissions savings of around 35%[109]. Given the inefficiencies of the current production process evidenced by the study (e.g., HEFA and ATJ were shipped from the US to Germany, and non-renewable energy supply was used during production), this is a substantial saving.

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