Synthetic/Sustainable Aviation Fuel Mapping - PUBLIC

Final Report

Scottish Enterprise

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Study period: September 2022 – March 2023

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Executive Summary

The aviation sector is at a critical juncture. Across the globe, aircraft manufacturers, airlines, governments and others are considering how best to decarbonise a sector that contributes to 3.5% of total anthropogenic warming. Replacing fossil-based aviation fuel with synthetic and sustainable aviation fuels (SAF) is seen as the best, if not the only, way to decarbonise the sector in the period to 2050 and beyond, as it can reduce carbon emissions by up to 80% over the lifecycle of the fuel and requires little, if any, changes to aircraft systems or the fuel supply infrastructure, while retaining all the performance characteristics of aircraft using conventional aviation fuel (CAF). Zero emission flight is the long-term ambition, through developing propulsion systems based on battery electric, hydrogen fuel cell electric or hydrogen combustion. However, these technologies currently have limitations in terms of potential range and/or a requirement for significant further development, validation and certification before they enter commercial operations. These are important considerations as the aviation sector includes many different sizes of rotary and fixed wing aircraft, some carrying a few passengers over a few tens of kilometres, others carrying several hundred passengers (and airfreight), over distances of several thousand kilometres.

There is, however, not enough SAF to meet current demand, and publicly known, planned production capacity is very unlikely to satisfy future demands. Recognising this gap, public and private sector organisations across the globe are investing significantly to ensure security of supply and capture market share. The period to 2030 will be critical for this, and Scotland, with abundant natural resources and established petrochemical expertise, has the opportunity to seize its share. The development of a local SAF manufacturing capability is also complementary to the Scottish national focus on hydrogen, thus building a unified decarbonisation strategy.

As an initial step, Scottish Enterprise has commissioned this study to understand the interest in and capability of industry and research organisations in Scotland to support a SAF supply chain that can serve both the domestic and international markets.

There are currently seven SAF production methods (plus two co-processing methods), that use a variety of waste feedstocks including used cooking oils, woody biomass, municipal solid waste and alcohol produced from waste biomass. In the future, power-to-liquid, or e-fuels, is expected to make the largest contribution – this combines hydrogen (from electrolysis of water) with captured carbon to produce simple hydrocarbons that are then further processed to produce SAF. Scotland has significant potential to produce power-to-liquid fuels, given its ambition for renewable electricity, green hydrogen and carbon capture utilisation and storage (CCUS).

SAF from existing processes is currently certified to be blended with CAF at volumes of up to 50%. This limit has been set due to the lower aromatic content in SAF compared with CAF, which reduces the efficiency of aircraft system sealing materials. There have been several demonstration flights using 100% SAF, but further work needs to be performed before 100% SAF blends can be certified.

Currently SAF only addresses 0.01% of the global market, but the expectation is that supply will grow to meet around 7.6% of the market demand within the next five years. This is driven by corporate social responsibility strategies and mandates being imposed by many Governments across the globe for a minimum percentage blend of SAF (typically between 2 and 5% by 2025) that will steadily increase towards 2050. The issue is that current and planned production facilities are unlikely to meet this demand – more need to be built. In fact, the International Air Transport Association (IATA) stated that in 2021, airlines have "purchased every drop of the 125 million litres of SAF that was available" despite its price being at least 2 to 4 times higher than that of conventional aviation fuel. This is before any mandates are in place.

Countries across the globe are adopting different strategies to stimulate and support SAF production and adoption, including through research and development (R&D) funding, capital grants, loan guarantees, tax credits (for producers and consumers), mandates, and 'book and claim' (where passengers pay a premium for SAF to support decarbonisation, while recognising that airlines may concentrate SAF supply to those airports/routes that have the highest demand, e.g., long-haul flights).

Individuals from a range of organisations from across Scotland, the UK and beyond were consulted as part of this study. These included organisations developing, blending and supplying SAF, aircraft manufacturers, airlines, airports, researchers and other stakeholders from the public and private sectors. In total, 45 individuals from 37 organisations were interviewed.

The key findings from this consultation are described below:

1. Most stakeholders believe that SAF will be essential in the period to 2050 (and beyond) to decarbonise the aviation sector, because it can directly substitute for CAF. Hydrogen combustion, on the other hand, needs significant development and validation of aircraft designs (at least ten years) before it can enter the market and much longer before it will become mainstream, while battery/fuel-cell electric aircraft are currently limited in range and size, although existing research and development (R&D) in this area promises higher energy density batteries by the mid-2020s that could extend range. This also takes account of aviation sector economics – aircraft are expensive and have relatively long service lives, meaning there will be a demand for fuel for aircraft in current fleets for at least the next 20 to 30 years. Most expect SAF to be in use for the majority of this century, at least for long-haul flights.
2. There are, however, many obstacles to overcome before SAF can have an impact on the aviation sector. Principle amongst these is that developing SAF technologies and building new plants is a very expensive business: £500M to £1B to build a 500kt p.a. plant which would take around five years to complete. Further, there are concerns over access to feedstocks which are also in demand from other industries, and the large energy requirements to produce SAF. In the long run, power-to-liquid is seen as the main production route for SAF, but the technologies to do so are still relatively immature.
3. There is a widespread opinion from stakeholders that the UK, as a whole, is not doing enough to ensure that it exploits the potential economic benefits from SAF. This is evidenced by the letters sent from industry leaders to UK Government Ministers at the end of 2022, that they expect there to be insufficient UK capacity to produce SAF and that, as a result, SAF will need to be imported to meet mandates, at a higher cost to airlines and therefore passengers. In contrast, the US, amongst others, was held up as an exemplar – providing significant incentives at Federal and State level to support investment in SAF plant development and SAF adoption.
4. The sector is unsure as to how the Scottish and UK Governments will support the adoption of SAF. There is a sense that the UK Government is not committed to a Contracts for Difference

(CfD) approach, that pays (or claims back) the difference between an initial agreed price and market price over a defined period of years, thus ensuring that the sector can grow to a commercially viable level. Without this (or something similar) the sector believes that there will be no incentive to adopt SAF until mandated to do so, which will be too late to drive domestic production.

5. Scotland has significant strengths that it could use to leverage economic impacts from SAF. These include an abundance of renewable energy and Scottish Government strategies to produce green hydrogen and support carbon capture utilisation and storage (CCUS) opportunities. These will be critical for the power-to-liquid routes. There are, in addition, several Scottish companies that are already, or could be, involved in the SAF supply chain.
6. There is, nevertheless, significant work to do to connect different pieces of the supply chain and provide the necessary support required. There is little SAF currently supplied into any of Scotland's airports, although all consulted have signalled a desire to transition towards it (and other low/zero-carbon options) as part of their clean air policies.
7. SAF production is already happening, elsewhere in the globe, and will continue to grow, however the window of opportunity to be part of this is narrowing – if action is not taken soon, it will be too late, others will capture the market, leaving Scotland in the role of buyer, which will inevitably drive up the cost of aviation.

This feedback was synthesised into the following SWOT analysis:

Strengths	Weaknesses
• Existing Petroineos refinery • Industrial expertise in SAF production • Early off-takers (Bristow and bp) • Existing oil & gas and aerospace engineering expertise • Strong aviation sector • Net Zero policy • Academic expertise (CCU, H2, biorefining) • SATE (Orkney)	• Fragmented supply chain/ lack of interest in parts • Lack of understanding amongst stakeholders • No incentive to adopt • Lack of clear UK Gov policy – mandate, incentives and investment (for plants) • Mixed messages from Scot Gov on decarbonising aviation • Feedstock – lack of clarity as to what will be available for SAF compared with other processes
Opportunities	**Threats**
• Not enough SAF to meet demand • Renewable energy • Green H2 – certified SAF first, P2L later • CCUS & DACC – but needs price reduction • Plans for CCUS and blue hydrogen at St Fergus • Demand from airports and end-users • Clear desire for local supply chain • Interest from SAF producers • Long-term need: 2050-70(+)	• Competition from other sectors for feedstocks (H2 & carbon) • Others in Europe (& UK) moving faster • SAF production and use is centralised (in UK) • H2 produced in Scotland, used elsewhere in UK • Certification (fuels and use in different aircraft) • Initial focus on long-haul may disadvantage Scotland

SWOT Analysis of the Scottish SAF Supply Chain

This was in turn used to elaborate several recommendations for further actions to exploit strengths and opportunities, and address threats and weaknesses:

1. Connect the (nascent) supply chain, as many who are, or should be, involved are having discussions and making plans in silos.
2. Bring others from outside Scotland into the network to discuss how the supply chain could be realised and supported, based on an initial SAF demand analysis.
3. Consider the development based on three scenarios:
    a. 'Full-steam ahead' – where there is strong public sector support for a Scottish SAF plant, that pulls in technology providers and a consortium of Scottish airports and airlines.
    b. 'Take it slow' – where the initial focus is on supporting the blending of (imported) SAF through tax incentives to reduce the cost of SAF to users and to build capability, capacity and demand across Scotland.
    c. 'Wait and see' – where Scotland continues to implement green electricity, green hydrogen and CCUS plans, thus laying the foundations for a future SAF supply chain. Further development decisions would be made on the basis of the outcomes from the SAF demonstration plants in England and Wales.

    These scenarios reflect different investment costs and risks, versus the risk of delaying too long and not realising the full economic impact to be gained from SAF. N.B., none of the major global players see a future scenario for decarbonising aviation that does not include SAF; so there will be a market.

    In this regard, a modular plant approach could be a way to demonstrate the practicality of a distributed SAF supply chain, for example, building demonstrator plants in different locations using different feedstocks, while at the same time supporting scale-up to that required for supply to Scotland's larger airports serving international routes.
4. In parallel to the SAF plant development, there could be RTD support and coordination to demonstrate that Scotland offers a good environment to develop and optimise technology for SAF production, and the necessary support and opportunities to exploit this further and commercialise.

Adopting the above recommendations would not only support SAF production; integrating green hydrogen and captured carbon utilisation technologies with renewable electricity could be the basis for the creation of hubs that share these resources to develop and produce different products for multiple sectors, thus addressing multiple priorities in Scotland's Net Zero ambitions.

The Scottish Government has the opportunity to be the driving force behind a SAF supply chain in Scotland. A clear message that it recognises the critical importance of aviation for both domestic transport links and international tourism, and the opportunity to decarbonise the sector through early adoption of SAF, would galvanise investment interest in Scotland.

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1 Introduction

1.1 Purpose of this Study

The main purpose of this study was to understand the interest in and capability of industry and research organisations in Scotland to support the adoption of synthetic/sustainable aviation fuels (SAF), which is seen by many, including the Scottish Government[1], as the first step towards decarbonising Scotland's aviation sector. It also aimed to gain a better understanding of global capabilities and market drivers for SAF.

Decarbonising transport is an important part of Scotland's ambition to be net zero by 2045 as it constitutes a significant component (36%) of annual greenhouse gas emissions[2]. Overall, emissions from transport are expected to fall by 41% by 2032 in Scotland. For road and rail transport there are clear avenues towards decarbonisation, mainly around electrification with hydrogen likely to play an increasingly important role in heavy duty vehicle (HDV) decarbonisation towards the end of this decade and the beginning of next. To a certain extent this is also true for maritime, where the electrification of vessels deployed on shorter routes is being considered, and fuels such as ammonia[3] are being considered for longer routes. Aviation, however, is much harder to decarbonise because of the lower energy density of batteries and hydrogen compared with fossil fuels, meaning range is compromised, and the high safety and reliability standards required. Nevertheless, the Scottish Government has signalled its intent to decarbonise scheduled passenger flights within Scotland by 2040. This will be an important component of the Carbon Neutral Islands strategy[4], given the essential role that aviation plays in maintaining connections between island and mainland communities.

The Scottish Government is supporting a number of initiatives for the decarbonisation of aviation, including Project Eilean[5] which aims to understand options for low-emissions aircraft servicing routes across the Highlands and Islands. This work identified opportunities to adapt existing aircraft to lower their emissions and the potential, as a result of increased passenger numbers and increased sustainability, to create up to 2,500 new jobs across the Highlands and Islands.

The Scottish Government also undertook a public consultation beginning in October 2021 (with results published in April 2022) to understand wider stakeholder views[6], for the purpose of informing Scotland's first ever Aviation Strategy. The consultation encompassed four topics:

- transition to low and zero emission aviation
- Scotland's international connectivity
- Scotland's domestic connectivity
- air freight

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1 https://www.transport.gov.scot/publication/disability-and-transport-findings-from-the-scottish-household-survey-1/transition-to-low-and-zero-emission-aviation
2 National Transport Strategy, (Scottish Government, 2020)
3 https://www.globalmaritimeforum.org/news/ammonia-as-a-shipping-fuel
4 A Fairer Greener Scotland. Programme for Government 2021-22 (Scottish Government, 2021)
5 https://www.digit.fyi/sustainable-aviation-could-create-2500-jobs-across-highlands-and-islands/
6 https://www.transport.gov.scot/publication/aviation-strategy-analysis-of-consultation-responses/

The present study focused on the first of these topics. The 93 stakeholders responding to the Scottish Government consultation showed particular support for electric and hydrogen powered aircraft, and also recognised the need for SAF, including domestic production, as part of the pathway towards zero emissions. This study addresses some of the questions raised during the Scottish Government consultation and aimed to:

- Define the market opportunities for SAF in Scotland and globally, in terms of:
  - Demand in Scotland and different global regions and for different applications (e.g., short haul domestic, freight vs passenger)
  - Companies and research groups that are leading SAF research, technology development and innovation (RTDI) around the globe
  - Policies that are supporting the development and deployment of SAF around the globe
  - Barriers to the development and deployment of SAF
  - International leaders in the production and distribution of SAF
- Identify Scottish capabilities in terms of:
  - Academic RTDI strengths that could support the decarbonisation of aviation
  - The company base, including locations, that could support the decarbonisation of aviation and the areas of particular interest for these companies that could lead to new projects
  - The current and future RTDI capabilities of these companies
  - Current and future appetite of these organisations to engage in the zero-emission aviation and wider decarbonisation of transport
- Identify ways in which these organisations could be engaged to support and develop the sector
- Suggest interventions that Scottish Enterprise and partners could undertake to maximise Scottish content in the transition to net zero emissions aviation via SAF

1.2 Study Methodology

The study had four main phases:

1. Defining the market opportunity
2. Mapping Scottish capabilities
3. Interview programme with key stakeholders including industry, business, research, government agencies and sector associations
4. Analysis of desk research and interview programme

These are each described below.

1. Defining the Market Opportunity

This included a review of:

- Government strategies
- Corporate strategies
- Major research programmes
- International strategies

This research identified what supply and value chain activities might be expected to support the development, production, delivery and deployment of, eventually, 100% SAF blends (from the current maximum allowed 50% blend). This phase also produced a supply and value chain schematic.

2. Mapping Scottish Capabilities

The supply and value chain schematic from the first research phase was used to map Scottish company and academic capabilities. These were identified from existing in-house knowledge, searches of relevant public databases (e.g., on Scottish Industry Directories) and through referral from others in Scottish Enterprise and those interviewed.

3. Interview Programme

A prioritised list was produced of companies, academic researchers and stakeholders to be interviewed. Interviews were based around the following discussion topics (not all were relevant for all interviewees):

- Current activities in the aviation supply chain
- Activities to date in SAF development/manufacture/use
- Opportunities and threats/barriers as a result of the adoption of SAF
- Any other considerations as a result of the adoption of SAF
- The extent to which the SAF supply/value chain can be domiciled in Scotland
- International (export) opportunities
- Wider opportunities to move towards decarbonisation of aviation within the next 10 years
- How public agencies could best support the Scottish industry base deliver sustainable aviation

The interview programme was undertaken between October 2022 and February 2023.

4. Analysis of Desk Research and Interview Programme

The output from both the desk research (points 1 and 2 above) and the interview programme (point 3) was analysed to identify current Scottish activities that support the realisation of SAF, and how these could be brought together within an overall supply and value chain. Further, the findings were used to synthesise a SWOT analysis of the Scottish ‘SAF ecosystem’, and from this to develop recommendations for actions to be taken to support a SAF supply and value chain in Scotland.

2 Global Strategies and Opportunities for SAF

The global aviation fuel market is estimated to be worth $217.18 billion in 2023 with a compound annual growth rate of 14.9%[7]. At its historical highest in 2019, the aviation industry consumed 7.5 million barrels (over 1 million tonnes) of jet fuel per day[8]. Fuel consumption fell dramatically following COVID-19 containment measures, however, the overall fuel appetite continues to increase and is predicted to reach 2019 levels by 2026 and then double by 2050.

The transport industry is estimated to be the second largest contributor to global greenhouse gas emissions (16.2%; Figure 1). The aviation industry is responsible for up to 2.5% of total CO_2 emissions (920 million tonnes) and contributes to 3.5% of total anthropogenic warming when non-CO_2 pollutants are taken into account[9].

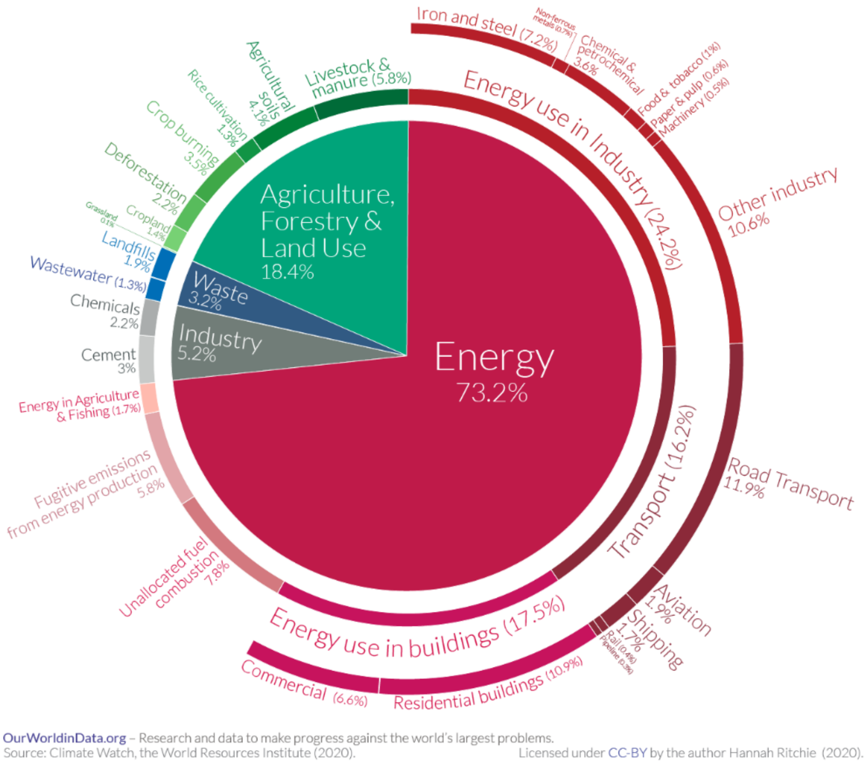

Figure 1: Global greenhouse gas emissions by sector based on carbon accounting data from 2016

In 2021, the International Air Transportation Association (IATA) committed to achieving net zero carbon by 2050, thus bringing 83% of the world's air traffic in line with Paris agreement objectives[10]. The replacement of conventional aviation fuel (CAF) with more sustainable alternatives is considered by the industry as central to decarbonising aviation. Sustainable synthetic aviation fuels (SAF) offer up to 80%

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[7] Aviation Fuel Global Market Report 2023 – Market Size, Trends, And Global Forecast 2023-2032 (The Business Research Company) . https://www.thebusinessresearchcompany.com/report/aviation-fuel-global-market-report

[8] https://www.bloomberg.com/professional/blog/jet-fuel-demand-gets-a-thrashing-until-2026/

[9] https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

[10] https://www.iata.org/en/programs/environment/flynetzero/

reduction in carbon emissions over the lifecycle of the fuel[11], and are therefore the key short-to-medium term solution to meeting net zero goals.

This section describes the current and emerging technologies for SAF production and policy initiatives aimed to promote SAF production and uptake. The current opportunities and issues associated with SAF uptake are discussed together with the forecast of the aviation propulsion future, with general trends visualised in Figure 2.

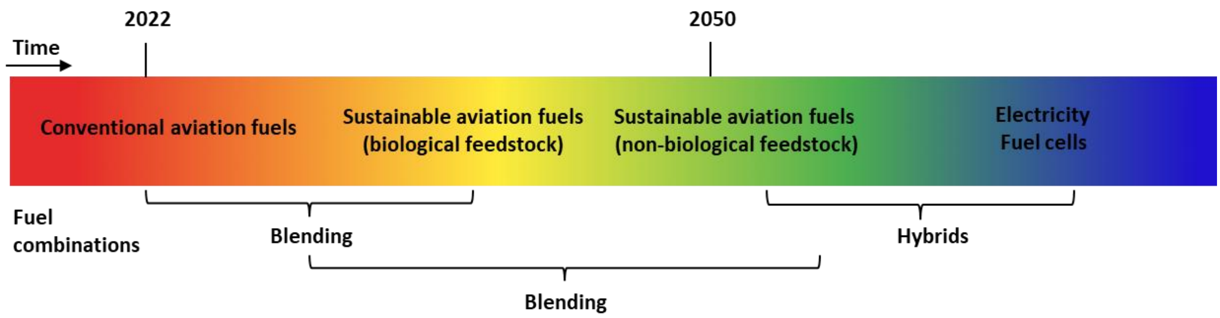


Figure 2: Sustainable aviation fuel adoption scenario. At present, CAF blending with SAF has begun, predominantly using SAF from a single biological feedstock.

In the short-to-medium term (five to ten years), the availability of each individual biological feedstock will reach its natural ceiling, largely because they are waste streams. In response, the policies will adopt to permit CAF blending with two or more types of SAF, as well as SAF blends without CAF. More 100% SAF-compatible planes will reach the market and become the dominant type of aircraft as the older aircraft retire. The opportunity to blend different types of SAF will drive down the price and increase SAF availability. Manufacturers will de-risk their processes by diversifying their fuel synthesis methods, likely in de-centralised sites in geographical proximity to the origins of feedstock.

By 2050, it is expected that CAF will represent a minor fraction of aviation kerosene (<20%) and will be confined to use in the longest-haul flights or in geographical locations where SAF is unavailable. Despite this, long-haul flights and commercial cargo planes will be fuelled predominantly with SAF.

The electric propulsion and fuel cell technological maturity will reach a scalable level. Small regional aircrafts in short-distance flights could be primarily powered by these zero-emission technologies with provision of appropriate infrastructure. Retrofitted multimodal engines capable of using fuel and electric or fuel cell systems will reach the market followed by purpose-built hybrids. This could result in a scenario where aviation fuel (SAF and CAF) is reserved for take-off and landing, and fuel cell or electric propulsion is used in high altitude cruising.

[11] https://www.bp.com/en/global/air-bp/news-and-views/views/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html

The remaining CAF production facilities, as well as other CO_2-emitting industrial sites will be equipped with in situ capture mechanisms that, in combination with hydrogen, will provide feedstock for synthetic fuel manufacturing. Direct air capture technology will be used to sequester residual CO_2 emissions.

Overall, the decarbonisation strategy is dictated by the size of aircraft and its flight distance (known as stage length). For shorter flights and smaller aircraft, battery electric and hydrogen technologies represent a viable opportunity. Presently, SAF is the only decarbonisation option for large aircraft and longer-haul flights (Table 1, Figure 3)[12].

	Battery-electric	Hydrogen (combustion and fuel cell)	SAF
The efficiency of fuel production and propulsion system	60%	25%	15%
Maximum predicted range in 2050	100-1,000 km	<2,500 km	No limitation
Expected large-scale market entry	2035-2040	2035-2040	<2030
Share of cumulative emissions reduction (2022-2050)	2-3%	8-22%	75-91%
Share of final energy demand in 2050	2%	13-32%	65-85%

Table 1: Decarbonisation options for aircraft[12]

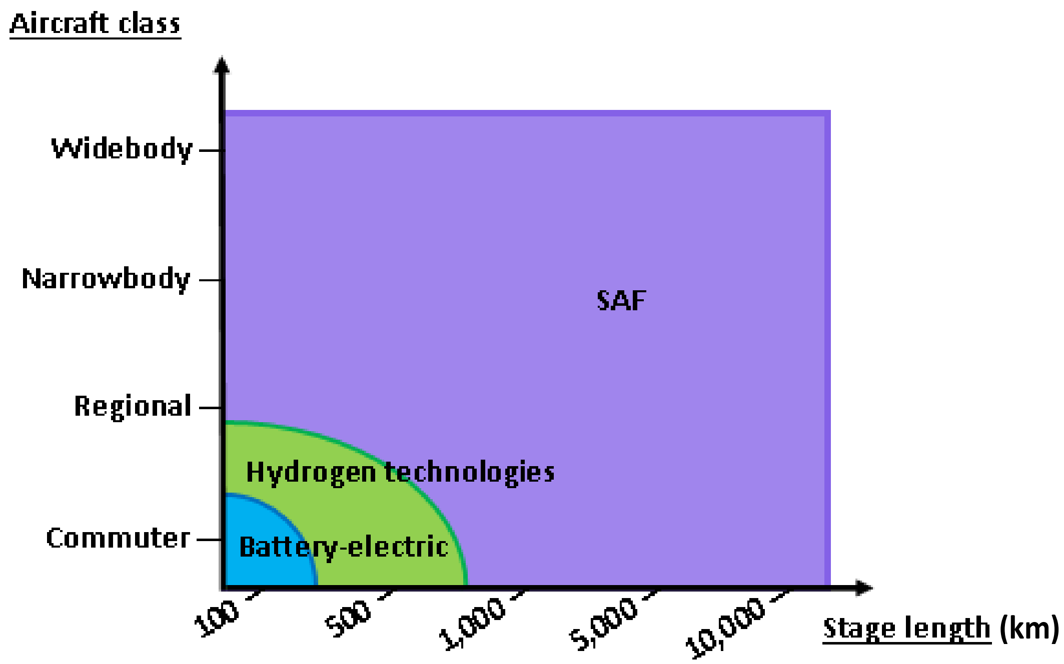


Figure 3: Range (stage length) of different classes of aircraft relative to different technologies[12]

[12] Adapted from: https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-the-aviation-sector-making-net-zero-aviation-possible

2.1 SAF Chemistry and International Regulation

According to international ASTM technical standards, aviation fuel is characterised using a range of physical and chemical properties, including volatility, fluidity, combustion-specific energy, and content of aromatic molecules and contaminants. In addition to meeting these specifications, SAF production methods are subject to additional regulation. At present, a total of nine fuel conversion processes are certified by ASTM D7566 for aviation use in current infrastructure (so-called drop-in fuels)[13]. Further to this, to qualify as sustainable, SAF must comply with ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) which includes a greenhouse gas lifecycle assessment of the feedstock[14].

There are currently seven certified SAF production methods (plus two co-processing methods). Table 2 provides an overview of these.

Conversion process	Abbreviation	Feedstocks	Certified blending ratio
Fischer-Tropsch hydro-processed synthesized paraffinic kerosene	FT-SPK	MSW & biomass	50%
Synthesized paraffinic kerosene produced from hydro-processed esters and fatty acids	HEFA-SPK	Bio-oils, animal fat, recycled oils	50%
Synthesized iso-paraffins produced from hydro-processed fermented sugars	SIP-HFS	Biomass used for sugar production	10%
Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	SPK/A	Waste biomass	50%
Alcohol-to-jet synthetic paraffinic kerosene	ATJ-SPK	Alcohols synthesised from biomass (such as starch)	30%
Catalytic hydro-thermolysis to jet fuel	CHJ	Waste oils	50%
Synthesized paraffinic kerosene from hydrocarbon hydro-processed esters and fatty acids	HC-HEFA-SPK	Algae	10%
Co-hydro-processing of esters and fatty acids in a conventional petroleum refinery	Co-processed HEFA	Fats, oils, and greases (FOG) co-processed with petroleum	5%
Co-hydro-processing of Fischer-Tropsch hydrocarbons in a conventional petroleum refinery	Co-processed FT	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

Table 2: Certified SAF conversion processes and their sustainable feedstocks

HEFA and ATJ-SPK are the largest-scaling processes; FT is also a significant contributor to the SAF pool, whilst the total SAF yield from the remaining technologies is marginal[15].

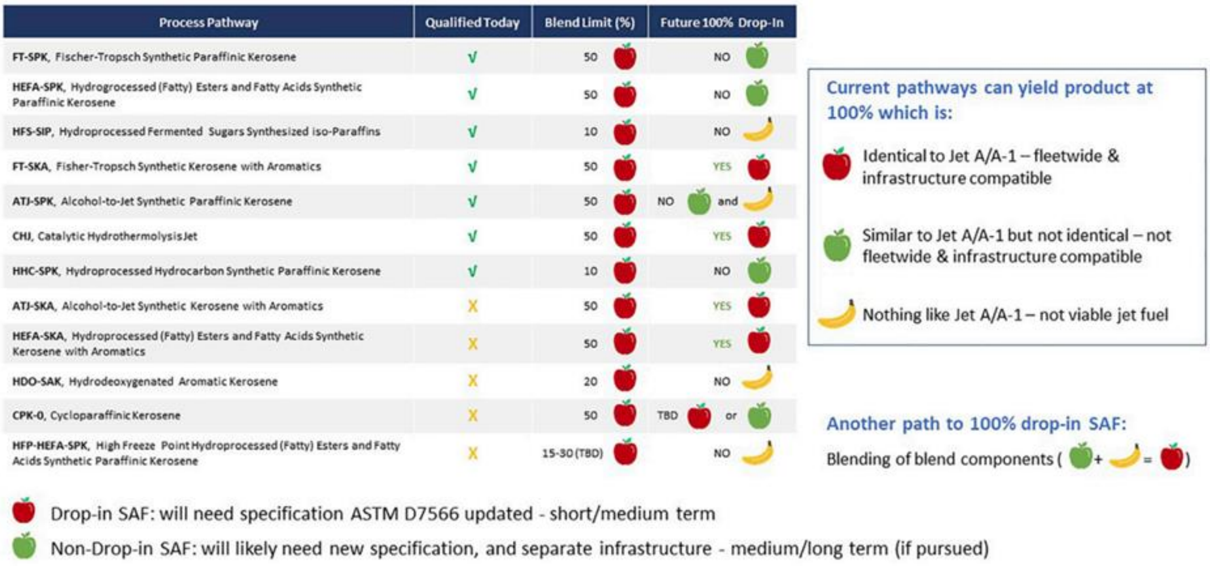
Presently, SAF is used in the aviation industry exclusively as a blending component of CAF. The regulations permit blending ratios up to 50%. This limitation is because pure SAF does not necessarily

13 https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx
14 https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2003%20-%20Eligibility%20Framework%20and%20Requirements%20for%20SCSs%20-%20June%202022.pdf
15 https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf

meet the ASTM technical specifications, especially in the aspect of the content of aromatic compounds. Aromatic compounds in aviation fuel are a double-edged sword: they are needed to ensure the swell of aircraft fuel system sealings; however, aromatics burn slower than other fuel components, thus contributing significantly to soot particulate emissions[16]. ASTM specifications dictate the aromatics content in jet fuel to be between 8% and 25%, however, the minimal concentration of aromatics needed for optimal seal swelling is unknown. This issue is further addressed by engine and airplane manufacturers (discussed in Section 2.2).

In correct mixing ratios, a blend of different types of SAF can meet the ASTM physical and chemical requirements for drop-in fuel (

Table 3). Whilst research shows that blends of SAF produced by different conversion methods are safe to use in terms of engine health[17], these are not yet approved by ASTM.



Process Pathway	Qualified Today	Blend Limit (%)	Future 100% Drop-In
FT-SPK, Fischer-Tropsch Synthetic Paraffinic Kerosene	√	50	NO
HEFA-SPK, Hydrogrocessed (Fatty) Esters and Fatty Acids Synthetic Paraffinic Kerosene	√	50	NO
HFS-SIP, Hydroprocessed Fermented Sugars Synthesized iso-Paraffins	√	10	NO
FT-SKA, Fisher-Tropsch Synthetic Kerosene with Aromatics	√	50	YES
ATJ-SPK, Alcohol-to-Jet Synthetic Paraffinic Kerosene	√	50	NO and
CHJ, Catalytic Hydrothermolysis Jet	√	50	YES
HHC-SPK, Hydroprocessed Hydrocarbon Synthetic Paraffinic Kerosene	√	10	NO
ATJ-SKA, Alcohol-to-Jet Synthetic Kerosene with Aromatics	X	50	YES
HEFA-SKA, Hydroprocessed (Fatty) Esters and Fatty Acids Synthetic Kerosene with Aromatics	X	50	YES
HDO-SAK, Hydrodeoxygenated Aromatic Kerosene	X	20	NO
CPK-0, Cycloparaffinic Kerosene	X	50	TBD or
HFP-HEFA-SPK, High Freeze Point Hydroprocessed (Fatty) Esters and Fatty Acids Synthetic Paraffinic Kerosene	X	15-30 (TBD)	NO

Current pathways can yield product at 100% which is:

Identical to Jet A/A-1 – fleetwide & infrastructure compatible

Similar to Jet A/A-1 but not identical – not fleetwide & infrastructure compatible

Nothing like Jet A/A-1 – not viable jet fuel

Another path to 100% drop-in SAF:

Blending of blend components (+ =)

Drop-in SAF: will need specification ASTM D7566 updated - short/medium term

Non-Drop-in SAF: will likely need new specification, and separate infrastructure - medium/long term (if pursued)

Table 3: SAF production processes, their certification status and blending limits, and the potential to be used as pure aviation fuel.

The red apples indicate fuels that can be drop-in, green apples are similar to drop-ins and may be usable in some existing aircraft but would require modification of the existing specifications and possibly infrastructure, and bananas indicate fuels that are completely different from petroleum-based kerosene and could not be used as stand-alone jet fuel in current infrastructure or equipment. Adapted from Kramer et al[18].

16 https://www.greenairnews.com/?p=2916

17 https://onlinelibrary.wiley.com/doi/full/10.1002/ceat.202000024

18 https://www.frontiersin.org/articles/10.3389/fenrg.2021.782823/full

2.2 Aeroplane Compatibility

The majority of current aeroplanes such as those manufactured by Airbus and Boeing, which constitute over 90% of the global fleet, and other aircraft using Rolls Royce engines, are compatible with up to 50% SAF blends[19,20]. Further to this, most leading manufacturers have pledged to make 100% SAF-compatible aeroplanes by 2030. From a practical point of view, this would involve using novel materials for engine sealings that do not require aromatic compounds for the swell function.

Several ground and flight tests have been conducted using 100% SAF, and it is now agreed that whilst fuel leaks due to insufficient sealing swell is a problem with older generation sealing materials (especially in the first 15-20 minutes of engine operation), SAF has no negative effects on overall engine health[21]. The first plane flown on 100% SAF was United Airlines Boeing 737 MAX 8: Chicago O'Hare to Washington Teagan National Airport (December 2021)[22] followed by Airbus A380 test aircraft MSN 1 Blagnac Airport, France using Rolls Royce Trent 900 engine[23] in March 2022. In November 2022, the RAF carried out the first-ever flight of a military aircraft fuelled entirely with SAF[24]. The 90-minute test flight of RAF Voyager (an air-to-air refuelling tanker) was launched from Oxfordshire in collaboration with Rolls Royce, Airbus, and AirTanker.

2.3 Current SAF Production Capacity

SAF manufacturing is a highly dynamic market composed of new and disruptive technology innovators, as well as already established oil refineries that are pivoting towards SAF production to address the growing demand.

The current global capacity of SAF production is difficult to estimate due to a range of factors that include refineries announcing their maximum capacity (and not the real output), co-production facilities where SAF is blended with CAF on site, and in public announcements, often SAF is not differentiated from other sustainable fuels such as biodiesel.

Roughly, it is estimated that SAF production will increase from only 5,200 tonnes in 2018 (ICAO) to 2.4 million tonnes in 2022 to mid-2023[25]. Despite this huge increase in production (over 4600% increase), currently, SAF addresses only 0.01% of the global jet fuel market[26]. Research that collates public announcements from global SAF manufacturers indicates that the theoretical maximum SAF production capacity in the near future (2-5 years) will be as high as 22.5 million tonnes (Figure 5)[27], or around 7.6% of the global jet fuel demand. This will further increase to 24 million tonnes by 2029, or 8% global jet

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19 https://www.rolls-royce.com/media/press-releases/2021/01-02-2021-business-aviation-rr-conducts-first-tests-of-100-precent-sustainable-aviation-fuel.aspx
20 https://www.airbus.com/en/sustainability/environment/climate-change/decarbonisation/sustainable-aviation-fuel
21 https://torroja.dmt.upm.es/congresos/asme_2011/data/pdfs/trk-4/GT2011-46572.pdf
22 https://www.ge.com/news/reports/united-flies-worlds-first-passenger-flight-on-100-sustainable-aviation-fuel-supplying-one
23 https://www.airbus.com/en/newsroom/press-releases/2022-03-first-a380-powered-by-100-sustainable-aviation-fuel-takes-to-the
24 https://www.gov.uk/government/news/royal-air-force-completes-world-first-sustainable-fuel-military-transporter-flight
25 https://www.sciencedirect.com/science/article/pii/S0016236122017471?via=ihub#b0390
26 https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/
27 https://www.argusmedia.com/en/hubs/sustainable-aviation-fuels

fuel demand based on currently available public information. This forecast is likely to increase as new facilities announce their expansions.

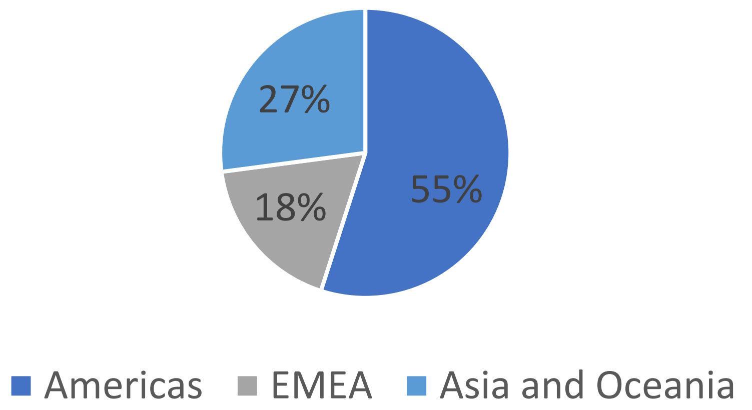
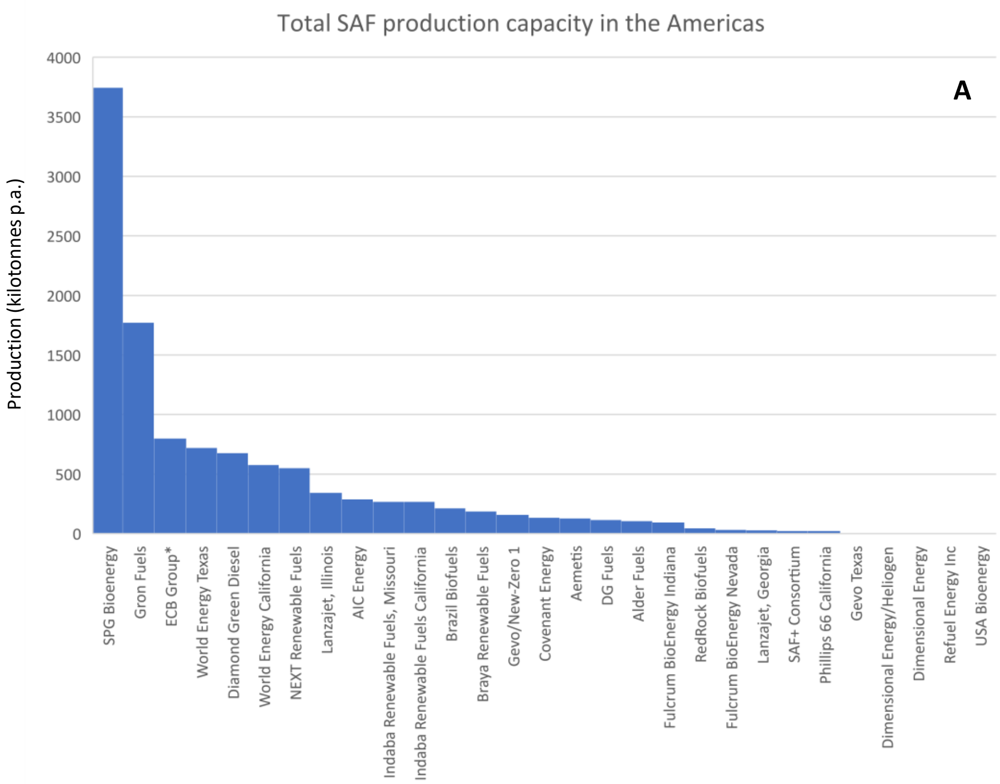
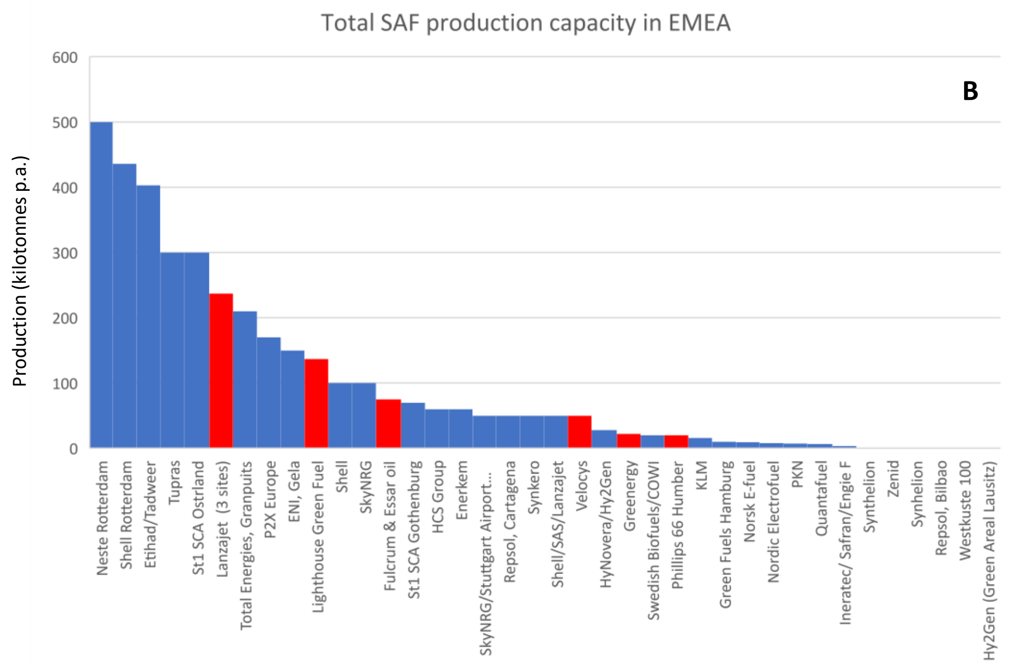


Figure 4: Theoretical maximum of global SAF production capacity based on manufacturers' self-reported active capacity within the next 2-5 years (tonnes annually). Adapted from Argus Media report "Demand for SAF continues to increase", October 2022[27]

Figure 5 A-C summarises SAF production facilities that have announced their manufacturing capacity. As before, this data relies on self-reported numbers of facilities which might include some that are not yet operative (such as SPG Bioenergy) and therefore the numbers are more indicative of SAF production capacity in the next 2-5 years.





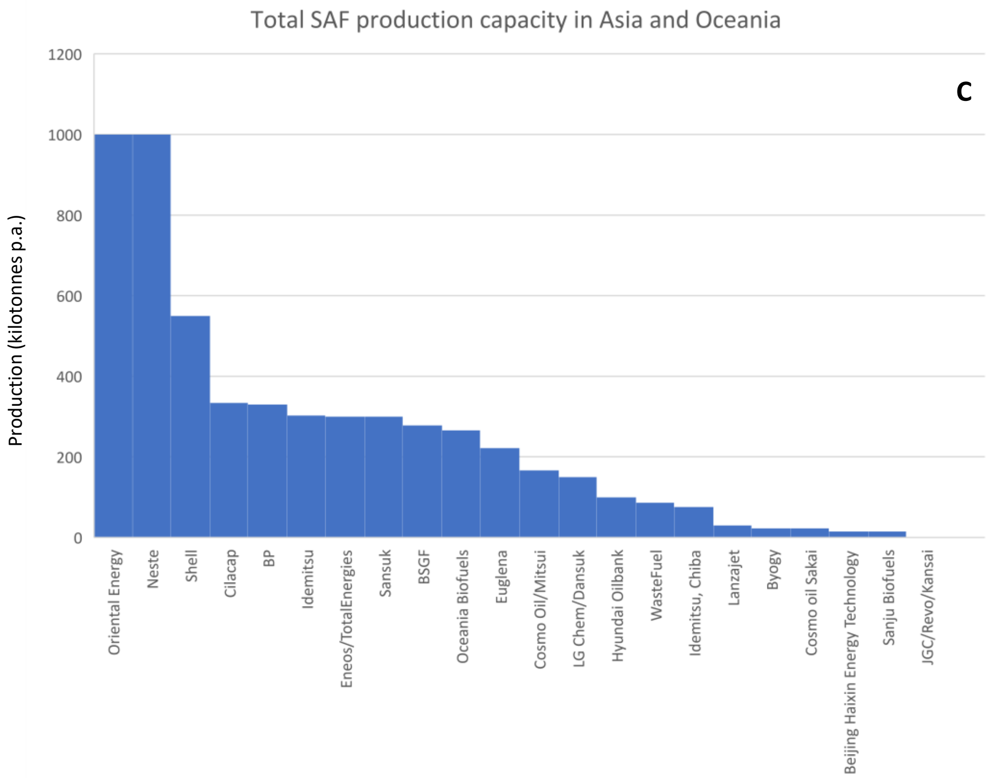


Figure 5: Production capacity of the major SAF producers in A – Americas; B – EMEA; C – Asia and Oceania (kilotonnes annually).

Figures representative of the SAF production capacity in the next 2-5 years. Red bars correspond to UK production sites. Adapted from Argus Media report "Demand for SAF continues to increase", October 2022[27]

2.4 SAF Policies around the World

SAF-related policies and mandates are being introduced internationally, and in the absence of government directives, many commercial organisations, including the members of the ICAO, have proactively announced self-imposed targets towards reaching net zero by 2050. SAF is universally recognised as a key element towards achieving this target. Countries around the world have taken a diverse set of approaches to enable domestic SAF production, and the main policy themes are summarised in Table 4 and discussed in detail below.

Funding	Incentives & tax relief for SAF supply infrastructure	Incentives & tax relief for SAF facility operation	Valorisation of SAF environmental benefits	Creating demand	Update existing policies to incorporate SAF	Enable SAF markets
Research & development funds	Capital grants	Blender's tax credit	SAF benefits under carbon taxation	SAF Mandates	National policies	Adopt sustainability standards
Development & deployment funds	Loan guarantees	Producer's tax credit	SAF benefits under cap-and-trade system	Mandate reduction in carbon intensity of fuel supply	Regional and local policies	Book-and-claim
	Investment tax credits	Support for feedstock supply				Support SAF stakeholder initiatives

Table 4: Strategies and SAF policies

2.4.1 The Americas

The US has been highly active in SAF policy development at both federal and national levels. The US Sustainable Skies Act 2021 (now absorbed in the Inflation Reduction Act) highlights a range of activities to achieve 3 billion gallons (9.2 million tonnes) of SAF production capacity by 2030, including research and development project fund up to $4.2 billion[28]. Algae feedstock technology projects (and consequently initiatives aimed at the certification of new SAF conversion processes) are eligible for further funding up to $35 million, thus suggesting that the government is interested in diversifying SAF feedstocks. Based on SAF production announcements from US fuel providers, a large proportion of SAF in the country will be produced using alcohol-to-jet technology by 2030 (LanzaJet and Gevo). Further, the Renewable Diesel and Sustainable Aviation Fuel Parity Act of 2022 allows SAF to qualify for loan guarantees under the Energy Policy Act of 2005. Overall, the US government aspires for SAF to meet 100% of aviation fuel demand by 2050 (approximately 108 million tonnes annually). Currently, there is no SAF blending mandate in the US.

Canada, Brazil, and Mexico support SAF development largely through government research funds and lobby groups. Canada's "The sky is the limit" challenge sponsored four projects up to $2.15M to

[28] https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

accelerate SAF production technologies[29]. The Canadian Council for Sustainable Aviation Fuels (C-SAF) represents over 60 airlines operating in Canada and works to promote SAF production in the local industry[30].

Similarly, SAF development is supported by Mexico's Sector Fund for Energy Sustainability (SENER-CONACYT)[31], Mexico's Bioturbosina[32], and Brazil Biokerosene Programme[33]. Brazil is the world leader in biofuels, and its approach to introducing more SAF into circulation is based on the emission reduction mandate as opposed to the volume blending mandate (which is the case with biodiesel and bioethanol)[34].

Some other countries in the Americas have a relatively low focus on SAF for meeting their sustainability targets. For example, Argentina National Sustainable Action Plan[35] prioritises natural gas and lithium batteries due to natural resource abundance; similarly, Chile strongly focuses on hydrogen manufactured with electricity from renewable sources (with the ambition to generate "the cheapest green hydrogen on the planet")[36].

2.4.2 Asia and Oceania

In Asia and Oceania regions, some countries have announced their SAF blending targets; for example, Japan Civil Aeronautics Act imposes a 10% SAF target mandate by 2030[37], and the Indonesian Aviation Biofuels and Renewable Energy Task Force is working towards a 5% biofuel mix by 2025[38,39]. On a government level, Indonesia further identifies the preferred future suppliers of SAF (Petramina and Wilmar Group). To protect its natural resources, Indonesia has announced a moratorium on new plantation land conversion from primary forest and peatland as part of the Sustainable Palm Oil mandate; this prevents primary forest lands being used for growing SAF feedstock. Other countries are still in the process of developing their SAF policies, such as New Zealand which is expected to announce a SAF blending mandate from April 2023[40]. China has published the Civil Aviation Green Development policy and Action thus committing to actively promote the deployment of sustainable aviation fuels and explore new development paths[41].

The Australian government is expressly working towards ICAO guidelines[42]. A study by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) in 2011 concluded that the

29 https://impact.canada.ca/en/challenges/green-aviation
30 https://c-saf.ca/
31 https://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=23
32 https://unitingaviation.com/news/environment/profile-cluster-bioturbosina-collaborative-effort-altfuels/
33 https://www2.camara.leg.br/legin/fed/lei/2021/lei-14248-25-novembro-2021-791992-publicacaooriginal-163943-pl.html
34 https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/agriculture/051822-brazil-saf-mandate-to-target-emissions-reductions-starting-in-2027
35 https://www.argentina.gob.ar/transporte/transporte-sostenible
36 https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf
37 https://asia.nikkei.com/Business/Transportation/Japan-targets-10-sustainable-jet-fuel-for-airlines-by-2030
38 https://www.icao.int/Meetings/altfuels17/Documents/4%20-Indonesia%20Initiative_Ministries.pdf
39 https://www.itb.ac.id/news/read/58191/home/indonesia-writes-a-new-history-by-conducting-a-successful-flight-trial-on-bioavtur-fuel
40 https://www.mbie.govt.nz/dmsdocument/18366-sustainable-biofuels-mandate-final-policy-design-proactiverelease-pdf
41 http://www.caac.gov.cn/en/HYYJ/NDBG/202209/P020220923528248199212.pdf
42 https://www.infrastructure.gov.au/sites/default/files/documents/managing-the-carbon-footprint-of-australian-aviation.pdf

Australasian region has sufficient biomass resources to achieve a 5% bioderived jet fuel share by 2020 and a 50% share by 2050[43]. The Australian Biofuels Research Institute, Biofuels Capital Grant Program, the Second-Generation Biofuels Research and Development Program (Gen2) and Strategic Framework for Alternative Transport Fuels and Future Fuels and Vehicles Strategy collectively work towards promoting innovation in new biofuel technologies and sustainable transport fuels, including aviation fuels[44,45]. Interestingly, Australian official communications highlight that the government sees SAF as an opportunity to reduce their reliance on imported jet fuel, and it is predicted that increased SAF production capacity could help avoid over A$9 billion of imports by 2050[44]. This principle is largely applicable to the UK that imports over 60% of its jet fuel[46].

2.4.3 Africa and the Middle East

In Africa and the Middle East, the lack of biogenic feedstock and, to some extent, low water security severely hinder the introduction of SAF into circulation. Whilst some countries have biofuel blending mandates for biodiesel (e.g., 3-5% in South Africa), it is yet to be elaborated to SAF. In South Africa the government has a strong focus on regulation and mitigation strategies for feedstocks to safeguard against compromising food security; for example, the use of first-generation feedstocks such as maize for fuel production is prohibited, and so is the cultivation of oil-rich crops considered to be invasive species (such as jatropha)[47]. Artificial irrigation of fuel feedstock is not permitted.

Therefore, governments, NGOs and entrepreneurs focus on the use of non-biological feedstock for SAF development. WWF South Africa/Africa-wide “Waste to Wing” project[48] that is funded by European Union’s Switch Africa Green Programme (€ 1.2 million), SkyNGR and others, aims to use municipal solid waste (MSW) for SAF production. Mauritania focuses on green hydrogen development[49], whereas Egypt and the Suez Canal economic zone have signed a memorandum of understanding aiming to establish projects on green ammonia in Sokhna (a $3bn investment) with priority on ship bunkering and later aviation[50].

The United Arab Emirates published the Power-to-Liquids Roadmap: Fuelling the Aviation Energy Transition in the UAE[51] highlighting the government’s strategic priority of hydrogen and CO_2 capture for SAF. The UAE possesses excellent solar power capabilities, but the storage capacity is a limiting factor. Further, water availability for green hydrogen production can be a further limitation; UEA sheikh and president Mohammed bin Zayed Al Nahyan has said that “Water is more important than oil for the United Arab Emirates”. On the other hand, the UEA has a precedent of implementing a carbon capture

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43 https://www.icao.int/environmental-protection/Documents/ActionPlan/Australia_en.pdf
44 https://publications.csiro.au/rpr/download?pid=csiro:EP107203&dsid=DS3
45 https://www.dcceew.gov.au/about/news/australias-future-fuels-and-vehicles-strategy-released
46 https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf
47 https://www.gov.za/sites/default/files/gcis_document/202002/43003gon116.pdf
48 https://www.wwf.org.za/?24801/Waste-to-Wing-project-first-to-enable-sustainable-aviation-fuel-production-in-South-Africa
49 https://bioenergyinternational.com/chariot-looks-to-develop-green-hydrogen-in-mauritania/
50 https://sczone.eg/the-prime-minister-witnesses-the-signing-of-mou-for-french-and-emirati-projects-to-produce-green-fuel-in-the-sczone/
51 https://www3.weforum.org/docs/WEF_UAE_Power_to_Liquid_Roadmap_2022.pdf

unit that is integrated into an iron and steel production facility (Al Reyadah), paving the way to carbon feedstock gathering for power-to-liquid SAF generation.

2.4.4 Europe

The European Union is developing some of the most ambitious sustainable aviation policies in the world. Under the Single European Sky and ReFuelEU Aviation legislative proposals, aviation fuel must include 2% SAF from 2025 rising to 85% by 2050[52]. Additional intermediate targets of this proposal include 6% from 2030, 20% from 2035, 37% from 2040 and 54% from 2045. Individual European countries are developing additional mandates: Norway 0.5% in 2022; Sweden 27% by 2030; France 2% by 2025, 5% by 2030; Netherlands 14% by 2030 and complete fossil fuel replacement by 2050. In addition to these targets, a sub-obligation for synthetic aviation fuels (0.7% in 2030, 5% in 2035 and increasing up to 29% in 2050) was included in the EC regulation in December 2022. These demand-enabling targets are further supplemented by anti-fuel tankering regulations, reporting obligations and financial penalties for failure to comply. The financial penalty revenue will be allocated to a new sustainable aviation fund to stimulate research and innovation in sustainable aviation technologies.

As of December 2022, the EU Parliament is seeking to widen the scope of the rules to include most EU airports and air carriers with 500 flights or more per year. An environmental labelling scheme will be developed by the European Aviation Safety Agency to incentivise consumers to travel in a more sustainable manner, and the European Union Emissions Trading Scheme (EU ETS) will be revised to accelerate the "polluter pays" principle by phasing out free allowances for the aviation sector. This, in combination with a more stringent assessment of non-carbon emissions, will provide a stronger economic incentive for the industry to reduce emissions[53].

These initiatives are both a great technological challenge and a unique business opportunity. The International Council on Clean Transportation (ICCT) estimate of EU jet fuel demand based on a 4.5% growth rate assumption is 55.5 million tonnes in 2025, 62.8 million tonnes in 2030 and 71.1 million tonnes in 2035. Considering the availability of biogenic resources, the EU possesses enough sustainable feedstock to produce the annual SAF output of 3.4 million tonnes by 2030 (5.5%)[54]. Therefore, one of the European strategic initiatives is focused on diversifying methods for SAF feedstock processing. The EC has excluded feed and food-based feedstocks from SAF definition. EC Horizon 2020 currently funds seven projects aiming to produce aviation kerosene from food waste, black liquor (paper production by-product), ethanol, and CO_2 + hydrogen[55]. Further, Horizon Europe has announced 25 tender calls for biofuels for aviation and shipping with a total of €5.8 billion invested in energy research and innovation in 2021-2022 and multiple other biofuel project funding sources are available for eligible participants [56].

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52 https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/saf-policy-actions

53 https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7609

54 https://theicct.org/sites/default/files/publications/Sustainable-aviation-fuel-feedstock-eu-mar2021.pdf

55 https://www.ecac-ceac.org/images/activities/environment/Switzerland_Action_Plan_on_CO2_Emission_Reduction_2021.pdf

56 https://energy.ec.europa.eu/topics/funding-and-financing/eu-funding-possibilities-energy-sector

2.4.5 UK

The UK has committed to reaching the SAF blending mandate of at least 10% by 2030, therefore growing the country's SAF demand to approximately 1.2 million tonnes annually. The mandate is due to be announced in mid-2023 and according to the Department of Transport consultation, it will be based on greenhouse gas emissions scheme (including tradable credits) as opposed to a fuel volume scheme. The obligation to meet the blending mandate will be the responsibility of aviation fuel suppliers.

Sustainable Aviation predicts that UK-produced SAF could provide between 3.3-7.8% of the UK's aviation fuel demand by 2035 (32% by 2050)[57]. With this capacity being below the 10% blending mandate, the UK is predicted to have a heavy reliance on SAF imports to close the gap. To address this the government has announced a significant investment towards UK SAF manufacturing facility development[58]. Overall, the UK's Jet Zero council committed to having at least five commercial-scale UK plants under construction by 2025. In December 2021, the Green Fuels, Green Skies competition awarded a total of £15 million to eight companies (Velocys, Nova Pangaea Technologies, Green Fuels Research, Fulcrum, alfanar Energy, Advanced Biofuel Solutions, and two Lanzatech projects) towards development of the establishment of a UK SAF industry. In 2022, the Advanced Fuel Fund competition granted a further £165 million to four companies (Lanzatech, alfanar Energy, Fulcrum, and two Velocys projects). These manufacturing facilities will be based in South Wales and England. Of note is the fact that no Scottish projects won any funding in this competition.

In addition to these projects, UK Government seeks to award £12 million to a SAF clearing house (a fuel testing centre) and the Breakthrough Energy Catalyst (£400 million). A further £1 million was awarded to Virgin Atlantic towards the delivery of the first ever net zero transatlantic flight in 2023[59]. In addition, key stakeholders continue to call on the UK Government for additional steps that will enable the UK SAF industry, thus creating more jobs and preventing imports in a highly competitive SAF import landscape; this was exemplified by a joint letter to the Secretary of State for Transport in November 2022.

2.4.6 Scotland

In Scotland, the government policies capitalise on offshore renewable energy, hydrogen and carbon capture as key tools for decarbonisation across all industries. Therefore, the industry has expressed interest in deployment of synthetic fuels (also known as e-fuels or power-to-liquid). Edinburgh Airport and renewable energy company Ørsted have signed a MOU to create an e-kerosene production site with capacity of up to 250,000 tons[60]. In October 2021 - April 2022, Transport Scotland carried out a consultation to help inform a Scottish Government Aviation Strategy[61]. The consultation revealed a notable appetite for domestic SAF production that could draw from the existing petrochemical skills provision, thus, enabling a more just transition towards net zero. Domestic SAF is particularly relevant in air freight where few alternatives exist at present. In contrast, key stakeholders called for overall reduction in aviation demand in international travel (via exploring other ways of connectivity), and there

57 https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf
58 https://www.gov.uk/government/groups/jet-zero-council
59 https://www.gov.uk/government/news/worlds-first-net-zero-transatlantic-flight-to-fly-from-london-in-2023
60 https://corporate.edinburghairport.com/media-centre/news-releases/airport-partners-with-orsted-to-bring-sustainable-air-travel-to-the-uk
61 https://www.transport.gov.scot/publication/aviation-strategy-analysis-of-consultation-responses/executive-summary/

was no agreement on the best way to decarbonise domestic air travel (with some preference for zero-emission aircraft).

In 2021, Project Eilean sought to investigate the technological and socioeconomic viability of a low emissions aircraft to serve the Scottish Highlands and Islands. The project concluded that for this application, hydrogen-based retrofitted powerplant systems are most likely to meet the requirements of energy-to-weight ratio in the medium term. However, the key technology that will help to decarbonise this air transport system is SAF, as a direct replacement of CAF.

These outputs will inform the ongoing development of the Scottish Government's Aviation Strategy.

Further details on public sector support in Scotland are provided in Section 3.

2.5 SAF Users and Buyers

Global SAF demand is exceptionally high. IATA states that in 2021, airlines have "purchased every drop of the 125 million litres of SAF that was available" despite its price being at least 2-4 times higher than that of conventional aviation fuel[62]. In 2020, the overall cost of jet fuel was $0.5 per litre. Meanwhile, the cost of SAF was $1.1 per litre ($8.67 /gallon)[63]. The global SAF demand will reach 22.7-32.8 million tonnes by 2030[64]. Sheila Remes, vice president of Environmental Sustainability at Boeing, has stated that "700 – 1,000 times more SAF is needed to meet this goal [net zero by 2050]" (330-450 million tonnes according to ATAG Waypoint 2050[65]).

SAF users and buyers are exploiting different strategies to ensure SAF demand in these conditions of scarcity. One popular strategy is locking SAF producers into multi-year supply contracts as buyer groups and alliances; some examples of such purchases are described in Table 5.

A novel development in this market is the "Avelia" SAF purchasing tool by Amex GBT and Shell. Avelia is a "book-and-claim" platform that allows business travellers to purchase SAF, therefore giving airlines access to the "buying capacity" of corporate customers who might be willing to pay a higher price for SAF in exchange for environmental benefits (that the corporate customer can then claim)[66]. This shows that the SAF market has a broad range of buyers that SAF manufacturers could serve.

In addition, this practice sets an interesting precedent: in case SAF is unavailable at a given airport, Avelia offsets SAF duty to another flight or facility where SAF can be purchased. If the policies for blending evolve along the same principles of SAF duty offsetting (i.e., if the wording of the regulation states that an airline as a whole must be 5% SAF as opposed to having a 5% SAF blend in each individual aeroplane), several novel strategies for SAF purchasing and distribution could evolve. In this scenario, SAF purchasing, use and distribution might accumulate around ten major European airports as opposed to SAF presence in regional airports, and there SAF could predominantly feed long-haul flights. This approach makes strategic sense considering that 80% of airspace industry emissions come from long-

62 https://www.iata.org/en/pressroom/2022-releases/2022-06-21-02/
63 https://simpleflying.com/saf-cost-competitive-jet-fuel
64 https://about.bnef.com/blog/2022-sustainable-aviation-fuel-outlook
65 https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/
66 https://www.businesstravelnewseurope.com/Air-Travel/Amex-GBT-and-Shell-team-up-to-create-SAF-buying-platform

haul flights[67]; by redirecting more SAF to fuel the longest flights, it is possible to achieve greater environmental benefits.

In addition to being the key buyers, airlines are some of the most significant investors in SAF production companies. Just to name a few: United Aircraft Corporation and Honeywell UOP have significant equity investments in Fulcrum Bioenergy and Alder Fuels[68]; Qantas and Airbus have announced a $200 million investment in Australian SAF facility development[69]; United Airlines is significantly invested in Cemvita and Oxy Low Carbon Ventures (carbon-capture technology firms)[70]. British Airways investments in LanzaJet in the US and Velocys in the UK[71], are likely to provide SAF for the company's transatlantic flights. This precedent is an opportunity for the Scottish aviation industry to get involved in inward investment to de-risk dependency on imported SAF (especially considering SAF-hungry neighbours with higher purchasing power such as Rotterdam and Heathrow).

67 https://aviationbenefits.org/media/167159/fact-sheet_2_aviation-and-climate-change.pdf
68 https://crreport.united.com/environmental-sustainability/emissions-reduction-sustainable-fuel-and-innovation
69 https://www.airbus.com/en/newsroom/press-releases/2022-06-qantas-and-airbus-joint-investment-to-kickstart-australian-biofuels
70 https://simpleflying.com/united-airlines-jet-fuel-from-thin-air/
71 https://mediacentre.britishairways.com/pressrelease/details/12796

Buyer	SAF goal	Producer	Volumes
Air New Zealand	10% by 2030	NESTE	1.2 ML/927 tonnes[72]
Narita International Airport/Etihad Airways	10% by 2030	NESTE (Finland)	NA[73]
Turkish Airlines	5% by 2030	NESTE	NA[74]
Aeromexico	NA	NESTE	40,000 litres[75]
Cebu Pacific	NA	NESTE	25 kilotonnes of blended SAF annually 2026-2031 [76]
The Oneworld Alliance (Alaska Airlines, American Airlines, British Airways, Finnair, Japan Airlines and Qatar Airways)	NA	Gevo	200 million gallons annually from 2027 [77]
JetBlue, Virgin Atlantic, Boom supersonic	NA	AirCompany (CO_2-derived fuel)	JetBlue: 25 million gallons over 5 years; Virgin: 100 million gallons over 10 years; Boom Supersonic: 5 million gallons annually[78]
LOT Polish Airlines	NA	PKN ORLEN	NA[79]
Cathay Pacific	10% by 2030	Aemetis	38 million gallons of 40% SAF blend from 2025[80]
Ryanair	12.5% by 2030	OMV	53 million gallons[81]
IAG (British Airways, Aer Lingus, Iberia, Level, Vueling)	10% by 2030	Aemetis	26 million gallons (unblended)[82]
Aer Lingus	10% by 2030	Devo	6 million gallons p.a. from 2026[83]
IAG Cargo and Kuehne+Nagel	NA	Phillips 66 Humber Refinery	8 million gallons[84]

Table 5: Publicly announced SAF purchases

72 https://www.neste.com/releases-and-news/renewable-solutions/air-new-zealand-welcomes-first-shipment-neste-my-sustainable-aviation-fuel-new-zealand
73 https://aci-apa.com/etihad-airways-takes-first-sustainable-aviation-fuel-saf-delivery-at-tokyo-narita/
74 https://aviationbenefits.org/newswire/2022/02/turkish-airlines-started-to-use-sustainable-aviation-fuel-on-its-flights/
75 https://www.airport-technology.com/news/aeromexico-sustainable-aviation-fuel/
76 https://simpleflying.com/cebu-pacific-saf-commercial-flights/
77 https://sustainabilitymag.com/renewable-energy/major-airlines-to-purchase-gevo-sustainable-aviation-fuel
78 https://simpleflying.com/jetblue-virgin-atlantic-boom-supersonic-saf/
79 https://simpleflying.com/lot-polish-airlines-to-purchase-domestically-produced-saf/
80 https://simpleflying.com/cathay-pacific-aemetis-saf-purchase/
81 https://simpleflying.com/ryanair-saf-deal/
82 https://simpleflying.com/iag-26-million-gallons-saf-power-flights-san-francisco/
83 https://simpleflying.com/aer-lingus-saf-purchase-gevo/
84 https://simpleflying.com/iag-cargo-saf-purchase/

2.6 Future Forecasts

Previous sections focused on SAF trends in the short-to-medium term. However, SAF technologies are rapidly developing and based on the current investment trends, several emerging aspects will influence the SAF market in the medium-to-long term.

2.6.1 Emerging SAF Conversion Technologies

Several emerging SAF conversion technologies of lower technological readiness levels (5-7) are being actively developed by researchers and SAF producers (Table 6).

Technology	TRL[85]	Feedstock	Description	
Power-to-liquid (electrofuels)	6	CO_2, green hydrogen and renewable electricity	Green hydrogen is generated using renewable electricity-powered electrolysis. Climate-neutral CO_2 (e.g., direct capture) is converted into feedstock (syngas or carbon monoxide); liquid fuel is then produced via FT reaction.	86
Carbohydrates-to-jet	7	Various types of carbohydrates such as sugar, lignin, cellulose	Similar to the certified SIP-HFS technology; improved strategies for carbohydrate polymer breakdown	87
Pyrolysis-to-jet	6	Any carbon-based materials: biomass, waste, plastic	Material is heated to extremely high temperature in absence of oxygen resulting in molecules dissociating into a crude oil-like product that can be recovered and re-synthesised into kerosene. As a by-product, hydrogen-enriched gas is produced that is useful for further synthesis.	88
Hydrothermal liquefaction	5	Any carbon-based materials: biomass, waste, plastic	Like pyrolysis-to-jet, but with more moderate temperature and higher pressure	89
Aqueous phase reforming	6[90]	Any carbon-based materials: biomass, waste, plastic; methanol	Biomolecules react with water under high pressure. Releases a large amount of hydrogen gas with methane, CO_2 and water as by-products that are captured and directed to SAF synthesis	91
Anaerobic fermentation	5 for aviation; 9 for other types of biofuels	Food waste, agricultural and forestry waste (depending on the microorganisms used in the production)	Fermentation exploits methanol, alcohol or syngas synthesis pathways present in many microorganisms. The biological product can be recovered and converted into fuel. Other biochemical pathways can be engineered into GMOs	92 93
Hydrogen combustion	5	Green hydrogen	Liquid or gaseous hydrogen is burned in a modified gas-turbine engine to generate thrust. It is important to note that hydrogen is not a drop-in fuel for aviation, therefore it cannot utilise the existing infrastructure for production, refuelling and safety assurance.	94 95 96

Table 6: Emerging SAF conversion processes

85 https://doi.org/10.1595/205651320X15816756012040
86 https://www.airbus.com/en/newsroom/news/2021-07-power-to-liquids-explained
87 https://www.sciencedirect.com/science/article/pii/S0016236122008985
88 https://www.sciencedirect.com/science/article/abs/pii/S0306261919310116
89 https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-31930.pdf
90 https://www.sciencedirect.com/science/article/pii/S2666790820300100
91 https://www.sciencedirect.com/science/article/pii/B9780444563521000064
92 https://www.sciencedirect.com/science/article/pii/B9780444563521000064
93 https://www.e3s-conferences.org/articles/e3sconf/pdf/2020/57/e3sconf_ati2020_05002.pdf
94 https://www.airbus.com/en/newsroom/stories/2020-11-hydrogen-combustion-explained
95 https://www.rolls-royce.com/media/press-releases/2022/19-07-2022-easyjet-and-rr-pioneer-hydrogen-engine-combustion-technology-in-h2zero-partnership.aspx
96 https://gtr.ukri.org/projects?ref=71165

The time that power-to-liquid and hydrogen combustion technologies will require to meet the desired scale in their markets heavily relies on governments' hydrogen[97] and renewable electricity strategies. Despite the low level of technological readiness, hydrogen-based propulsion strategies (power-to-liquid, fuel cells and hydrogen combustion) have a high potential to disrupt the SAF field in the medium-to-long term (after 2030) due to the effectively unlimited potential of fuel synthesis if provided with enough green hydrogen and electricity. It is already hypothesized that the use of power to liquid fuels is likely to be reserved exclusively for aviation[98]. Hydrogen-powered aviation is a major strategical focus in the European Union[99] and especially Germany[100]. A power-to-liquid fuel blending sub-mandate is being discussed in the EU which potentially provides a unique market opportunity for Scotland due to closely aligned hydrogen-focused national energy initiatives.

2.6.2 Hybrid Technologies

Hybrid-electric aircrafts could become the intermediate stage of aviation transition away from CAF. By hybridising propulsion sources, the fuel burn is further reduced, and the infrastructure wins time to prepare for an all-electric aircraft in the longer term. Daher has stated that hybrid aircrafts will reach the market in the next six years[101]. In these aircraft, electric motors will be used in cruise flights, whereas SAF combustion engines will be deployed when more power and electric motor recharge are required. Other companies, such as Magnix, offer diversification of hybrid systems that include kerosene-electric and hydrogen fuel cell-electric hybrid aircrafts. Surf Air Mobility plans to retrofit hybrid electric systems onto small private aircrafts (the Cessna Grand Caravan) aiming to reach the market by 2024[102].

2.6.3 All-electric Technologies

All electric technology is an appealing candidate for small aircraft and short distance journeys. Currently, all-electric passenger aircraft capacity is approximately nine seats[103]. A US-based aircraft manufacturer Pyka recently unveiled an all-electric autonomous cargo aircraft with 180 kg maximum load capacity and 200-mile range designed to facilitate deliveries over rough terrain[104]. In Scotland, unmanned and drone all-electric aircrafts are being trialled for delivery applications by Sustainable Aviation Test Environment (SATE) consortium[105], and AGS Airports in collaboration with NHS Scotland (project CALEUS)[106]

Overall, these engines could be of particular interest to regional airlines that often feature very small aircraft and distances less than 500km[107]. Rolls Royce, Tecnam, and Widerøe (the largest regional airline in Scandinavia) aim to deliver all electric passenger aircraft by 2026 to serve the extensive network of

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97 https://research.csiro.au/hyresource/policy/international/
98 https://www.transportenvironment.org/wp-content/uploads/2020/12/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf
99 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
100 https://www.bakermckenzie.com/en/insight/publications/2021/08/sustainable-aviation-fuel-and-german-ptl-roadmap
101 https://www.ainonline.com/aviation-news/business-aviation/2022-10-18/daher-sees-hybrid-electric-aircraft-later-decade
102 https://labusinessjournal.com/transportation/aviation/surf-air-mobility-enters-race-green-air-travel/
103 https://www.theguardian.com/environment/2023/jan/09/electric-planes-sound-like-a-fantasy-but-they-may-be-the-future-for-short-haul-in-australia
104 https://uk.motor1.com/news/650844/pyka-pelican-cargo-debut/
105 https://www.hial.co.uk/homepage/21/sustainable-aviation-test-environment
106 https://www.agsairports.co.uk/drones
107 https://www.cnbc.com/2019/06/18/all-electric-jet-firm-eviation-announces-us-airline-as-first-customer.html

short take-off and landing airports present within the islands and remote regions[108] that is somewhat similar to Scottish geography.

German company Evia Aero has purchased 25 all-electric planes from Eviation Aircraft[109] and 10 hydrogen fuel cell planes from Cranfield Aerospace Solutions[110] in a bid to get ahead of the curve in developing technology integration in the German aviation industry.

Aircraft and engine manufacturers have expressed similar interests. Rolls-Royce has stated their "ambitions to be the leading supplier of all-electric and hybrid electric propulsion and power systems across multiple aviation markets", thus outlining the predicted medium-to-long-term trend in aircraft propulsion systems[111]. Similarly, GE aims to develop the largest electric propulsion powertrain system (350kW) over the next two years, working towards a 2MW powertrain to increase the flight distance and reduce the weight of the batteries[112]. In the longer term (2040-2070), the use of SAF will likely be confined to long-haul flights and large and airfreight aircraft.

108 https://www.tecnam.com/rolls-royce-and-tecnam-join-forces-with-wideroe-to-deliver-an-all-electric-passenger-aircraft-ready-for-service-in-2026/

109 https://www.prnewswire.com/news-releases/eviation-announces-evia-aero-order-for-25-all-electric-alice-aircraft-301653493.html

110 https://www.e-pages.dk/weserkurier/167260/article/1624212/19/1/render/?token=9f3edb9e04f848ab94a7767077b7c736&vl_platform=ios&vl_app_id=com.newscope.weserkurier.PDFReader&vl_app_version=5.4.3

111 https://www.mtdmfg.com/news/rolls-royce-to-create-300-jobs-with-80m-investment-in-aviation-batteries/

112 https://www.ge.com/news/press-releases/ges-efforts-to-build-2mw-powertrain-for-commercial-electric-flight-gain-altitude

3 The SAF Supply Chain in Scotland

3.1 Defining the Synthetic/Sustainable Aviation Fuel Supply Chain

The supply chain for SAF can be described as follows:

- R&D in research organisations on production methods for SAF, including chemical and biobased synthesis from captured greenhouse gases and bioresources
- R&D on aircraft systems including fuel systems, engines, and monitoring/control systems to enable efficient and safe use of 100% SAF blends
- Manufacturing and blending of SAF (with CAF)
- Manufacturing of new aircraft systems, sub-systems and components to accommodate 100% SAF blends
- Retrofitting existing aircraft to operate with 100% SAF
- Aircraft maintenance and repair
- Distribution of SAF, which may include an increased number of regional production and distribution hubs
- Airlines and aircraft owners
- Airports and airport services

In turn this supply chain is supported by a number of different organisations including:

- Research and technology organisations, such as universities and innovation centres
- Investment and finance to support both RTD and capital expenditure, this includes work by the Enterprise Agencies to support RTD on new SAF technologies and to engage with key sector stakeholders in Scotland, across the UK and abroad to understand what is needed to build a SAF supply chain in Scotland
- Trade bodies that represent the wider aerospace and fuel sectors
- Policy – including Government Agencies with a remit for the transport and aerospace sectors, including fuel use, and expert groups established to advise such agencies

3.2 Overview of the SAF Supply Chain in Scotland

There are many organisations that could *potentially* support a SAF supply chain within Scotland, but relatively few that are currently positioned to do so. These are organisations that have sites within Scotland and for which one or more of the following statements are true:

- Already part of or engaged with the aerospace sector
- Undertaking RTD towards low-carbon/net zero fuels including SAF

These organisations are listed in Table 7.

RTD SAF Production	Manufacture & Blending of SAF	RTDI & Manufacture of aircraft systems/ subsystems	O&M	Distribution of SAF	Aircraft owners & airlines	Airports & services
• iGTL • Zero Petroleum • Drochaid Research • Sustainable Energies Scotland (SESL) • HiiROC/ Zeleno • Nova Pangaea	• Petroineos • Argent Energy • bp • Exxonmobil • Shell	• Rolls Royce	• MB Aerospace • Belcan • Woodward • GE Caledonian	• Air bp • Gulf Aviation • Shell Aviation • ExxonMobil	• Bristow Helicopters • RAF • Loganair • BA • Ryanair • EasyJet	• Edinburgh Airport • AGS Airports • Highlands and Islands Airports • Oban & the Isles Airports • Prestwick Airport

Supporting Organisations			
RTOs	**Finance**	**Trade Bodies**	**Policy**
• HWU – H_2, CCU to methane, biogas • STRATH – solid waste to power, fuel & chemicals • GLA – biomass to energy • EDI – marine biorefining to biogas & ethanol • ABD – catalysts for bioprocessing, power to methane • SATE (Kirkwall Airport) – demonstrated various low/zero carbon flight technologies	• SNIB • Inward investment • SE, HIE, SoSE	• ADS Scotland • BAG (Scottish Region)	• Aerospace Defence Industry Leadership Group • Transport Scotland

Table 7: Potential Scottish Supply Chain for SAF.

N.B. these organisations are not yet necessarily pursuing SAF, but either are considering it or could, because of their activities, be involved in a SAF supply chain. Furthermore, this is not an exhaustive list, there may be other organisations that could be engaged in a Scottish SAF supply chain.

Abbreviations: AGS (Aberdeen, Glasgow and Southampton Airports), HWU (Heriot Watt University), STRATH (University of Strathclyde), GLA (University of Glasgow), EDI (University of Edinburgh), ABD (University of Aberdeen), SATE (Sustainable Aviation Test Environment), ADS (Aerospace, security, Defence and Space), BAG (British Aviation Group)

4 Industry and Stakeholder Consultations

In total, 83 individuals from 58 organisations were contacted for interview with 45 consulted from 37 organisations. This is summarised in Table 8 and a list of organisations that were consulted is provided in Appendix A.

Organisation Type	Contacted		Interviews Completed	
	Organisations	Individuals	Organisations	Individuals
Company	34	48	19	21
Academic	8	10	5	5
Stakeholder	16	25	13	19
Total	**58**	**83**	**37**	**45**

Table 8: Overview of Number of Organisations and Individuals Contacted for Study

Overall, there was clear sentiment that Scotland is a leading nation in the transition to net zero and has a strong aviation sector. There was recognition that all of the pieces to build a SAF supply chain are already present in, or could be attracted to, Scotland.

The key points that can be taken from the interviews can be grouped as follows:

1. Most interviewees believe that SAF is essential in the period to 2050 (and beyond) to decarbonise the aviation sector. Hydrogen combustion needs significant development and validation before it can become mainstream, and battery/fuel-cell electric aircraft are currently limited in range and size
2. There are, however, many obstacles to overcome before SAF can have an impact on the aviation sector
3. There is a widespread opinion that the UK, as a whole, is not doing enough to ensure that it exploits the potential economic benefits from SAF
4. Clarity is needed from the Scottish and UK Governments on how the adoption of SAF will be supported
5. Scotland has significant strengths that it could use to leverage economic impacts from SAF
6. There is nevertheless significant work to do to connect different pieces of the supply chain and provide the necessary support required
7. SAF production is already happening and will continue to grow, however the window of opportunity to be part of this is narrowing – if action is not taken soon, it will be too late, others will capture the market, leaving Scotland in the role of buyer

These points are discussed below.

4.1 The Importance of SAF

SAF was acknowledged by all who were interviewed as making the largest contribution to decarbonising aviation over the coming decades. The main reason for this is that it can directly substitute for conventional aviation fuel with little or no modification to either the fuel formulation or the aircraft systems. This means that existing infrastructure, in terms of supplying fuel to airports and refuelling of planes at airports, does not need to change.

This also takes account of the aviation sector economics. Aircraft are expensive and have a relatively long service life, with 20-30 years not being uncommon, following second and even third resales. Furthermore, it takes at least ten years to modify, test and validate even existing aircraft designs and bring new designs (e.g., Boeing Dreamliner) to the market. As a result, most aircraft in operation are legacy (e.g., ~80% of Airbus planes), which means they will require access to aviation fuel for potentially several decades to come. Several interviewees also commented that SAF is a more homogenous and cleaner fuel; so likely to lead to lower maintenance requirements from aircraft and fewer particulate emissions than CAF.

While battery, hydrogen fuel cell and hydrogen combustion (and various hybrid combinations) have the potential to disrupt this, many of those interviewed believe that these will only have niche applications in the 2030s and even by the 2070s, aviation fuel (mainly SAF) will still be required for long-distance flights. The reasons for this include:

- Range – mainly for battery electric flights, which are likely to be only suitable for up to a few hundred kilometres, although improvements in battery energy density, through new chemistries expected within this decade, could help extend range[113]. However, the range of hydrogen fuelled aircraft was also questioned, with the longest flights (e.g., London to Sydney) requiring at least one stopover for re-fuelling (FlyZero).
- Aircraft re-design and certification – even re-designing a conventional aviation fuel powered aircraft is a lengthy process (ten years) and there have been examples of issues with new planes after they enter service (e.g., Boeing Dreamliner and 737 MAX[114]). Designing a new plane, to run on a different type of fuel, introduces significant challenges. The main issue with using hydrogen is the need to cryogenically store it to keep it liquid and therefore at a higher density. Most designs are opting for large tanks that take up considerable space in the hold area of the aircraft. These are larger than the equivalent jet fuel tanks and also need to be ballistic proof. These designs need to consider how to manage changes in weight distribution as the hydrogen is used up during flight (current jet fuel aircraft have fuel distributed in the wings, in the underbody and in the tail). Airbus is also pursuing an alternative blended wing design that could allow more distributed hydrogen storage, but due to the novelty in design, this would require even greater testing, validation and certification efforts.

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[113] High-energy battery technologies (Faraday Institution, 2020)
[114] https://www.aviationpros.com/aircraft/commercial-airline/news/21272509/whats-holding-back-boeings-787-dreamliner

Figure 6: Airbus ZEROe Concept Blended-Wing Aircraft[115]

- Longer term impacts on the operational life of aircraft – there are also concerns that not enough is known about how the thermal management of cryogenically stored hydrogen might have on structural components of the aircraft.
- Hydrogen infrastructure – it is not sufficient to design, validate and certify a hydrogen turbine aircraft, there also needs to be adequate infrastructure in place for its refuelling. This is not just restricted to origin and destination but to other points where an aircraft may need to be diverted due to any number of reasons, e.g., passenger illness, systems fault, weather, etc. If hydrogen is not available at the site the plane is diverted to, it potentially becomes a stranded asset, that is expensive to recover.

Over 75% of those interviewed, including aircraft manufacturers, operators and airports, are of the opinion that SAF will be in use beyond 2050, for intercontinental flights at least. Some believe it will be used for the majority of this century, due to the limitations with other known technologies. For those focused more on short-haul/sub-regional flights there was a keen interest in battery and fuel-cell electric. There was also recognition, that once hydrogen technologies are sufficiently tried and tested, then they would likely take over as the dominant powertrain. However, this is likely to be in the 2050s at the earliest.

More than 50% of those interviewed agree that SAF produced from different feedstocks and using different process technologies will be required, at least over the next five to ten years to meet blending mandates. Some believe that by 2050 power to liquid (P2L or e-fuels) will be the dominant source of SAF, while others believe that we will still be using significant volumes of other feedstocks, given the additional energy requirements to produce hydrogen and capture carbon. In this regard, some are concerned about the UK Government limits imposed on HEFA (hydro-processed esters and fatty acids) generated fuels, which is a mature technology, considering the scarcity of supply.

In terms of the future, some respondents were confident that newer SAF technologies would realise more significant carbon reduction, with the following quoted by one company:

- Best HEFA process ~80% reduction

115 https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

- P2L ~90% reduction
- Waste to Fuels (WtF) with carbon sequestration ~150% reduction (i.e., net negative)

4.2 Many Obstacles to Overcome

Despite the optimism and overall support for SAF, there was acknowledgement that there are still many obstacles to overcome. Principle amongst these is that developing SAF technologies and building new plants is a very expensive business. Various companies that are in the process of doing so, or have considered the costs, stated costs of between £500M to £1B to build a 500kt p.a. plant which would take around five years from "first spade in the ground" to production. This, together with significant operating costs (in terms of sourcing and processing feedstock, including energy consumption), make SAF plants a significant investment that is difficult to secure private finance for, given that it is an immature industry. This highlights the second obstacle – a lack of clarity from Government as to how SAF consumption will be promoted over CAF and other technologies. Without this long-term certainty it will be difficult to secure the private investment necessary for building and operating plants.

There is also recognition that all the feedstocks that have been described are also feedstocks or resources for other sectors, including chemical manufacturing, energy supply and even fuels for other transportation sectors (e.g., HEFA technologies are also used to produce biodiesel). In this regard, SAF technologies require significant input of feedstock and energy, for example:

- A 500kt WtF plant needs ~1Mt of MSW each year to operate, of which ~50% is removed during pre-processing stages
- The plant requires ~0.5MJ of electricity/energy input to produce 1MJ of SAF
- A P2L plant, however, would need 2.5MJ energy to produce 1MJ SAF and this would be 3MJ if Direct Air Carbon Capture (DACC) was used

So, to fully embrace SAF production considerable excess renewable energy is a pre-requisite.

Over 75% of those interviewed believe that there are sufficient feedstocks, at least to the early 2030s. The key question is what happens after this:

- Feedback is that there is sufficient MSW in the UK to operate around 50 plants, and that this could be transported over considerable distances. Moreover, the plant designs are such that they can operate with other feedstock, if necessary, as the expectation is that volumes of MSW will decrease in the 2030s due to decreased landfill and increased recycling. There is also competition from Waste to Energy (WtE) plants. P2L is a transition that companies could adopt in the longer term, as this also includes FT processes.
- Agri and forestry arisings are used by some companies to produce SAF. While this model works well in Scandinavian and N. American countries where there is abundant resource, it remains to be seen whether this will be truly scalable in the UK, due to the distributed nature of the feedstock.
- Waste oils and food/drink by-products are another key feedstock for fuel producers. However, in the UK, at least, this is directed towards the production of biodiesel and chemicals, and as mentioned above, there is concern that the UK Government is restricting this feedstock through a desire to diversify the supply chain.
- CO_2 and H_2 are the largest potential resources, with the caveat that their generation and processing to SAF is highly energy intensive. However, even here, there are multiple demands.

H_2 is being proposed for industrial fuel switching, grid back-up and other forms of transportation (e.g., HDVs), while captured carbon could be a feedstock for construction materials and chemicals manufacturing.

A further consideration is that most of the companies developing SAF technologies and establishing demonstration plants are micro/small and lack the capacity to manage more than one project at a time, which means that build-out is slow. In the UK these companies are focusing on major hubs with existing infrastructure, as identified by the winners of the Advanced Fuels Competition: Fulcrum, LanzaJet, Velocys and alfanar which are in Humber, Merseyside or South Wales.

Finally, there is a recognition that some types of SAF, particularly those that lack aromatic compounds, may require aircraft components to be redesigned or manufactured with different materials. This could potentially be a significant effort for legacy aircraft and may require new validation and certification of such parts before they enter service.

4.3 UK is Falling Behind

There is real concern among many in the industry that there will not be enough SAF to meet the UK's 10% blend mandate by 2030, and a sense of urgency to address this, as evidenced by the letters that industry leaders have sent to the UK Government over the last few months. Many are concerned that even with the recently announced Advanced Fuel Fund winners there will be too few plants in operation by the end of this decade and that domestic SAF supply will be constrained during the 2030s, leading many to speculate that Scotland and the rest of the UK will need to import from other countries that are far more advanced with their plans (e.g., the USA or the Netherlands). This is consistent with the observation that many airlines are tying suppliers into multi-year purchase agreements for SAF (see Table 5) – there is deep concern that there will not be enough to satisfy mandates.

Allied with this is concern from a number of those interviewed that, despite investments (e.g., in the Advanced Fuel Fund competition), UK Government policy at the moment seems to be to leave SAF development to market forces. This could cause significant issues because it fails to acknowledge the high investment, high risk nature required to make SAF a reality – in short, it will not deliver SAF at the scale and price-point required.

Over 75% believe that other countries are more advanced in terms of policy for SAF. For example, the EU announced changes to the ETS in December 2022, which will see free ETS permits for the aviation sector cut by 25% in 2024, 50% in 2025 and removed altogether in 2026. What this means is that by 2026 airlines will need to purchase permits for any CAF that is used. Revenues from this scheme will go into an innovation fund to support further decarbonisation and to support the sector's transition to SAF, 20 million free ETS permits will be made available between 2024 and 2030 for airlines that start using SAF. Altogether this aims to address the price difference between SAF and CAF.

Many of those interviewed would like to see the UK mandate a percentage of SAF in all fuel dispensed to aircraft. However, the current mandate is that suppliers meet a certain percentage blend overall, which suggests that they will likely concentrate their supplies to the biggest (international) users, for example London Heathrow (LHR).

Many of the companies that have developed SAF technologies are also pursuing opportunities across the globe, and several indicated during interviews that they will go where the policy is most supportive. In this regard, there is significant interest in N. America, particularly the USA, and increasing interest in

Australia and the Middle East. However, even smaller countries are being successful in attracting interest from SAF developers. For example, the Irish Government is supporting a pre-feasibility study between SkyNRG, Boeing, Avolon and Orix Aviation to determine the possibility of developing a SAF supply chain and refinery in Ireland[116].

4.4 Clarity is Needed

What is needed most of all from the UK and Scottish Governments is clarity. Those interviewed recognised that aviation is reserved to Westminster but felt that there were opportunities for Scottish Government intervention. Stakeholder feedback suggests a perception that the UK Government is not fully behind a contracts for difference (CfD) approach for SAF, which most believe will be necessary to secure investor confidence. The view from industry is that the Government may be concerned about the risk of fraud, for example, that an airline claiming a CfD payment for SAF on international flights operating out of the UK, may in fact be sourcing that SAF from outside the UK, i.e., bunkering, where a plane carries more fuel than is necessary for flight because the costs of fuel at its destination are higher than its origin.

There is lack of clarity regarding how the mandate will ensure access to affordable SAF across all UK aviation, if it is directed towards a target volume blend in a supplier's overall jet fuel operations, which can be achieved through supplying a slightly higher percentage blend to the largest consumers, such as LHR.

As a result of all of this, the SAF price trajectory is unclear, and most consumers will not adopt SAF until the mandate is in force (currently 2030) with others only doing so if it is part of their corporate social responsibility (CSR) agenda. This is too late to drive the demand that is needed to, in turn, provide confidence to the market. There is currently no financial incentive due to the cost difference nor obligation without the mandate.

Finally, the lack of clarity regarding future policy and regulations is a significant barrier in terms of:

- How different SAFs are defined and whether they will be treated equally under different regulations, e.g., the renewable transport fuel obligation (RTFO)
- Whether (and when) it will be possible to blend SAFs originating from different feedstocks
- Guarantees that the regulatory framework will not change within a period commensurate with investment payback (likely 20 years or more)
- Ensuring a level playing field between countries and in particular the UK vs EU incentives, as SAF producers want to be able to trade on international markets

4.5 Scotland has Strengths

The interviews highlighted a number of Scottish strengths that could be supported and exploited to develop a SAF supply chain.

Most notable is the abundance of renewable energy, and in particular offshore wind. Together with the Scottish Government stated ambitions to produce green hydrogen and support carbon capture

[116] https://skynrg.com/avolon-partners-with-global-aviation-leaders-to-launch-sustainable-aviation-fuel-feasibility-study-in-ireland/

utilisation and storage (CCUS) opportunities, this sends a strong signal to industry looking to develop P2L plants, as it addresses the key barriers of feedstock the availability and cost of renewable electricity. The ambition to be a net exporter of both hydrogen and electricity, and perhaps import captured carbon for storage in disused North Sea oil and gas fields, also addresses industry requirements for security of supply. In this regard, the EU has signalled an appetite for e-fuels specifically (as shown in the sub-mandate in December 2022) and this could be a potential export market for Scotland. Of course, all of this is dependent on the captured carbon, green hydrogen and electricity being available for this purpose.

There is already the potential for a SAF production industry in Scotland:

1. iGTL has patented its SAF production technology and already produced small volumes at EMEC for an RAF demonstrator project[117]
2. EMEC itself has produced hydrogen which could be supplied to others as feedstock for SAF production[118]
3. Nova Pangaea Technologies is partnering with LanzaTech as one of the Advanced Fuel Fund competition winners, and can use forestry and agricultural arisings and whisky by-products as feedstock. It has previously worked with Scottish sawmills[119]
4. Drochaid Research has already been involved in SAF projects, to modify existing and develop new catalysts that improve FT process efficiencies, and is, therefore, an asset for a Scottish SAF supply chain[120]
5. SESL, a start-up based in St Andrews, is developing novel catalysts to improve FT processes for gases produced from different feedstocks. Their technology is currently at lab-scale, however, they aim to establish a 0.5MW gasification plant on the Eden Campus (St Andrews)[121]
6. There was interest from some interviewed companies in establishing production plants in Scotland, contingent on securing the right sort of support

There is also an existing refinery in Scotland, Petroineos, which supplies CAF to most of Scotland's airports. Although not currently producing SAF itself, it is arguably the key potential supply chain participant, given its existing capabilities and capacities, and was mentioned, as such, by several of those interviewed.

Another potential site is St Fergus, where Storegga Technologies have plans for CCUS and hydrogen production, initially blue but transitioning to green as more offshore electricity becomes available. This then highlights another important asset – Scottish expertise in oil and gas and downstream processing, together with infrastructure (e.g., pipelines) and supporting academic expertise in oil and gas, power networks and hydrogen.

It also plays well to the vision that most stakeholders (over 75% of those interviewed) have for SAF production – that of a distributed network where it is produced near feedstocks (that are inexpensive) and the (valuable) SAF (or at least the crude, which is fairly homogenous, particularly if using FT

117 https://www.emec.org.uk/projects/hydrogen-projects/igtl-synthetic-gasoline-demonstration/
118 https://www.emec.org.uk/facilities/hydrogen/
119 https://www.biofuelsdigest.com/bdigest/wp-content/uploads/2021/02/RDPack12-NovaPangaea.pdf
120 https://www.drochaidresearch.com/716-2/
121 https://gtr.ukri.org/projects?ref=10045292

processes, regardless of feedstock) can then be transported around the country. All expect there to be more SAF plants than existing petrochemical refineries.

The RAF could be an important partner in all of this. RAF Lossiemouth is one of the largest bases in the UK and its fuel use is expected to increase due to larger aircraft that are being introduced for North Sea surveillance. The RAF recently undertook a 100% SAF demo flight[122], and are very interested in P2L modular refineries that could produce hundreds to a few thousand litres of fuel and be deployed to frontline positions. All of their fuel supplies are awarded competitive contracts, agreed centrally through the Defence Strategic Fuel team in Bristol. Given past collaborations, e.g., with iGTL and EMEC[123], the RAF is potentially a strong partner for demonstrating new technologies in Scotland.

4.6 Fragmented Supply Chain

Despite the strengths, it is evident that the current ecosystem is fragmented. The current supply of SAF into Scotland is limited, with Air bp supplying small volumes to Aberdeen Airport (for Bristow Helicopters operations to bp rigs in the North Sea).

Overall, the strategy being adopted by key (potential) players seems to be more of a wait and see.

This suggests that there is an immediate opportunity to better network the sector, including all stakeholders in the supply chain (Table 7). An outcome from this could be to bring customers together to stimulate demand and broker off-take agreements.

Airports could have a significant role to play here, with their 'clean air policies' driving up the need for a greater percentage of SAF in planes operating from them. However, this also needs to recognise that all will be competing with other airports which could have an economic advantage if they do not adopt the same policies, e.g., seeing operations and passengers shifting from Glasgow and Edinburgh to airports in the North of England. Feedback suggests that at least a 10% demand for SAF would be required to justify investment.

4.7 Narrowing Window of Opportunity

The evidence from our literature review and supported through consultations is that there is an increasingly limited time to act to develop capability, while addressing numerous issues. For example, building a SAF plant is predicated on:

1. Fuel security, which is one of the drivers for Government support.
2. Blend mandate, which will drive consumer demand for SAF.
3. Ensuring security of feedstock supply.
4. Permitting, which should facilitate rather than hinder the building / expansion of SAF plants.
5. Other supportive policy, such as, loan guarantees, tax relief, ensuring price stability through CfD or perhaps the ETS, and time-limited/milestone dependent guarantees. It was suggested that with the appropriate measures in place, plants that are not performing according to plan could be shut down and investment (and kit) channelled elsewhere.
6. Well-defined customer demand, over an extended number of years.

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[122] https://www.gov.uk/government/news/royal-air-force-completes-world-first-sustainable-fuel-military-transporter-flight
[123] https://www.emec.org.uk/projects/hydrogen-projects/igtl-synthetic-gasoline-demonstration/

Altogether these make a strong business case, including reliable income projections over 20 years, that is the period of time generally stated as being needed to ensure a return on investment (RoI), and thus essential for securing private investment.

Feedback from industry indicates that there is a finite time to act and if the opportunity is not seized then other countries will do so, and Scotland will miss out on the economic impacts including job creation. These issues need to be addressed mainly at a UK level, but with opportunities for Scottish Government interventions to be considered, particularly around points 5 and 6, which could help incentivise investors. In this regard, it must be recognised that SAF plants represent significant investment, which is at relatively high risk, for the moment at least. Public support needs to be considered in order to leverage private investment. Once this risk is mitigated, i.e., when a few plants have demonstrated successful commercial scale operations, then more private investment will follow.

Finally, although the Scottish Government's Minister for Transport (Jenny Gilruth) has clearly stated the importance of the aviation sector to Scotland's economy, including international trade and tourism, and the role that SAF will play in the decarbonisation of the sector[124], there are still some in the sector that feel that it is not receiving the priority that it should, and that there are mixed messages regarding the means by which decarbonisation will be achieved. This has recently been captured in a report from the Aviation Cross Party Group, published in March 2023[125], that calls on the Scottish Government to have a goal for SAF and clearer strategy linking aviation and the net zero policy. The expectation is that this position will be clarified when the Scottish Government publishes its first ever aviation strategy in the coming months.

4.8 Costs and Projections for the Sector

The cost of building a SAF plant is expensive, between £500M and £1B indicated by interviewees for a 0.5 to 0.6Mt p.a. plant, and time-consuming with 5 years or more from initial plans to commercial production. The interview programme also highlighted some other considerations:

1. MSW based plants require about 1Mt MSW p.a., from which ~0.5Mt of refined waste (~50-65% organic matter) is expected to enter the process stream.
2. There is the opportunity to adjust processing parameters in plants, such as WtF, that use gasification and FT processes, to allow them to accommodate different feedstocks. However, the key issue is security of supply of any feedstock (it is not a trivial process to adjust to different feedstocks).
3. Carbon emissions are also being pursued as feedstock – initially from point sources (industrial stacks) which are more economical than DACC. However, they may not remain so as point emissions reduce in number and volume over the coming decades, due to industrial decarbonisation.
4. P2L has lower CAPEX than other SAF manufacturing processes (e.g., HEFA, WtF) but higher OPEX, mainly due to energy demands.

124 Article in The Airport Operator, Winter 2023

125 The Recovery of Sustainable Aviation, Travel & Tourism in Scotland (Aviation Cross Party Group, March 2023). The Aviation CPG comprises: Scottish airports, international airlines, sector associations and other related businesses. It is convened by Paul McLennan MSP and Graham Simpson MSP

5. DACC, is seen in the long run as being important (when other feedstocks are depleted and when there are fewer point emissions). It can be twinned with various SAF processes to either enhance production or to provide the carbon source for P2L. However, DACC currently costs between $350-600 per tonne of CO_2 captured, making it at least 3-5x more expensive than CAF.
6. A 500kt DACC plant costs more than $500M plus $200-300M for an FT or ATJ plant and ~2-3 years from spade in the ground until production. Altogether from plans to delivery this would take ~6 years.

Overall, it is likely that, for Scotland, initial SAF uptake will be from private jet users, cargo and book and claim (particularly business class). In the longer-term there are opportunities for refuelling short and long-haul commercial flights, as well as providing SAF to the RAF.

Despite the costs, there was consideration that carbon capture, eventually including DACC, could result in technology convergence around 'EcoParks' where the captured carbon (plus green hydrogen and electricity) could be used by complementary technology companies for different needs, for example, traded for carbon credits, feedstock for SAF, fine chemicals or to be used in food production. DACC is generally perceived as being necessary to remove remaining hard-to-abate emissions, and so investment in DACC plants will be required at some point in the future. This could, however, provide added value to Scotland's Net Zero ambitions as such 'EcoParks' or hubs, and their basic building blocks of DACC, green electricity and green hydrogen production can be reconfigured, repurposed or upgraded to meet a variety of future manufacturing, carbon capture or energy storage as required. Unlike other infrastructure investments, such as building a plant to manufacture specific chemicals, such hubs offer a larger degree of flexibility in their input and output, and could be re-configured in the future to meet different needs.

5 SWOT Analysis

The findings from the desk research and interview programme have been synthesised into the following SWOT analysis.

Strengths

- Existing Petroineos refinery
- Industrial expertise in SAF production
- Early off-takers (Bristow and bp)
- Existing oil & gas and aerospace engineering expertise
- Strong aviation sector
- Net Zero policy
- Academic expertise (CCU, H2, biorefining)
- SATE (Orkney)

Weaknesses

- Fragmented supply chain/ lack of interest in parts
- Lack of understanding amongst stakeholders
- No incentive to adopt
- Lack of clear UK Gov policy – mandate, incentives and investment (for plants)
- Mixed messages from Scot Gov on decarbonising aviation
- Feedstock – lack of clarity as to what will be available for SAF cf other processes

Opportunities

- Not enough SAF to meet demand
- Renewable energy
- Green H2 – certified SAF first, P2L later
- CCUS & DACC – but needs price reduction
- Plans for CCUS and blue hydrogen at St Fergus
- Demand from airports and end-users
- Clear desire for local supply chain
- Interest from SAF producers
- Long-term need: 2050-70(+)

Threats

- Competition from other sectors for feedstocks (H2 & carbon)
- Others in Europe (& UK) moving faster
- SAF production and use is centralised (in UK)
- H2 produced in Scotland, used elsewhere in UK
- Certification (fuels and use in different aircraft)
- Initial focus on long-haul may disadvantage Scotland

Figure 7: SWOT Analysis of the Scottish SAF Supply Chain

5.1 Strengths

- Existing Petroineos refinery – providing infrastructure, expertise and supply chain connections (including international via Forth Ports). The INEOS site is also very likely to have space available to build a SAF plant.
- Industrial expertise in SAF production – in various companies that are already involved in CAF production, distribution and use, and in companies that are developing or supporting the development of new SAF production processes.
- Early off-takers (Bristow, bp, and RAF) – demonstrating that SAF can deliver in real world conditions.
- Existing O&G and aerospace engineering expertise – particularly around Aberdeen, Fife and Grangemouth.
- Strong aviation sector – all the airports were strongly supportive of SAF adoption and have had at least bi-lateral discussions with others in the supply chain.
- Net Zero policy – that will deliver hydrogen, captured carbon and green electricity that could be used for SAF production thus decarbonising aviation and further contributing to net zero ambitions.

- Academic expertise (CCU, H_2, biorefining) – particularly at Heriot Watt, Strathclyde and St Andrews, and with IBioIC as a strong linker and networker.
- The Sustainable Aviation Test Environment (SATE) (Kirkwall Airport) – has demonstrated various low/zero carbon flight technologies including drone technologies to deliver mail, packages and medical supplies to remote islands (Windracers project), and hybrid electric flights for Ampaire (between Orkney and Wick/John O'Groats).

5.2 Weaknesses

- Fragmented supply chain/ lack of interest in parts – at the moment, there is limited bi-lateral discussions with no concerted engagement across the supply chain, thus there is no real understanding of what the scale of domestic demand could be and how best to engage with non-domestic customers.
- Lack of understanding amongst stakeholders – about the need to maintain a competitive aviation sector and that the only technology that can make significant impacts over the short to medium term is SAF. There needs to be greater dialogue and engagement to address this.
- No incentive to adopt – SAF is 2-5 times more expensive that CAF. Given the ongoing difficulties facing the industry post-COVID, there is little real incentive to take on additional burdens when these are not mandated or called for (by customers).
- Lack of clear policy from the UK Government – on the precise terms, conditions and timings of the mandate, incentives and investment (for plants).
- Perception that the Scottish Government is unclear about how the aviation sector should be decarbonised which will not encourage inward investment, and could make manufacturers more likely to look to other parts of the UK or abroad to establish plants.
- Feedstock – lack of clarity as to what will be available for SAF compared with other processes, and whether some feedstocks will be treated more preferentially (e.g., better financial incentives) or not.

5.3 Opportunities

- Not enough SAF to meet demand – customers (airlines and aircraft owners) around the globe are binding suppliers into multi-year contracts to ensure they have sufficient SAF going forward. Projections from various industry and sector bodies suggest that globally there will not be enough SAF to meet a 10% mandate in 2030. As a result, Scottish plants should be able to secure commitment from off-takers as part of any initial investment plan.
- Renewable energy – Scotland is predicting a significant surplus of green electricity in the 2030s, at least some of which could be directed towards SAF production via P2L.
- Green H_2 – Scotland aims to be a hydrogen exporter, however, some of this could be used for SAF production, initially via existing, certified SAF production methods, with P2L later. This can be used domestically to decarbonise aviation and exported to other regions and countries. Given the vast potential renewable energy from Scotland, this could be ramped up to meet demand.
- CCUS & DACC are technologies that are planned to be adopted at different locations in Scotland as part of the Net Zero Strategy. These could be used to provide feedstock for SAF production, and at the same time could help drive down costs for carbon capture through economies of scale.

- In this regard, Storegga Technologies' plans at St Fergus represent a key opportunity – a nexus for carbon capture utilisation and storage (CCUS), hydrogen production and green electricity generation, alongside the existing oil and gas infrastructure and local expertise.
- Demand from airports and end-users is clearly there across all major Scottish airports.
- Clear desire for a local supply chain from users to ensure competitive prices and security of supply.
- Interest from SAF producers – due to Scottish Government policy and availability of feedstocks and power.
- Long-term need: 2050-70(+) – any investment now will be making a return for at least 30 to 40 years.

5.4 Threats

- Competition from other sectors for feedstocks (H_2 & carbon) – the ambitions for hydrogen and electricity cover many different uses and sectors including both the domestic and export markets. It is not clear whether there will be sufficient to meet all these needs, what will be prioritised, and the timings involved.
- Others in Europe (& UK) moving faster – users will take SAF from where they can get it, meaning those suppliers are then incentivised to expand further. The general consensus is that the US is progressing at a far faster rate than the UK.
- SAF production and use is centralised (in UK) – current UK SAF developments are focused at a few locations in England to serve the main airports. These could be further developed if nothing is done within Scotland, meaning that SAF will be supplied from England to Scotland at a higher cost.
- H_2 produced in Scotland, used elsewhere in UK – hydrogen has a value itself and given the ambition to produce large amounts in the 2030s, could be seen as a stable supply for use in SAF production elsewhere in the UK.
- Certification (fuels and use in different aircraft) – there is still a significant lack of clarity regarding how and when different types of SAF will be certified for blending with CAF, use on their own or blended with other types of SAF.
- Initial focus on long-haul may disadvantage Scotland – this could direct most of the SAF supply to larger UK airports: Heathrow, Gatwick and Manchester, meaning that either little, if any, SAF is available to decarbonise flights from Scottish airports or that fuel costs are more expensive from Scottish airports.

6 Conclusions and Recommendations

It is clear that major economies across the globe are actively pursuing SAF to decarbonise their aviation sectors and secure economic returns. Yet, we are at the beginning of this journey, and no nation has, so far, fully captured this opportunity. Scotland is ideally placed to do so. It has a solid foundation on which to build a SAF supply chain, in terms of a strong and engaged aviation sector, existing infrastructure, oil and gas expertise, and highly relevant RTD capabilities. There is also evident demand for SAF from domestic users and potential for export. This is actively supported by the Enterprise Agencies through RTD programmes and engagement with domestic and international stakeholders. The Scottish Government strategy for Net Zero, including plans for green electricity, green hydrogen and CCUS have been identified as exemplars by those stakeholders engaged in this study. However, these activities are not yet joined up, and in order for Scotland to capitalise on its strong foundations it will need a concerted effort from both the public and private sectors, particularly around the significant investments that will be required to realise a SAF supply chain. The intention of this report is to assist in the development of such an Action Plan to realise this ambition.

There are significant weaknesses and threats, however, that could prevent these opportunities being realised. Below we provide some recommendations for how these could be addressed.

1. **Lay the Foundations for Supply Chain Development**
   It is clear that, to a large extent, those that are part of the existing CAF supply chain and/or have a strong potential to be part of a future SAF supply chain are having discussions and making plans in silos. As a result, many are unaware of others' intentions and as such there is no clear picture of what the overall demand for SAF could be in Scotland. For example, airports need to engage with each other, to understand each other's plans and present a consolidated demand to suppliers. This of course also requires input from airlines operating from Scotland's airports.
   There is a need for the public sector to facilitate the active engagement of all airports and airlines operating in Scotland in the first instance.
   Key outputs could be a stronger and more informed Scottish network, with better multi-lateral connections. This could also deliver an initial demand analysis.
2. **Build the Network**
   The next step would be to bring others including suppliers and potential technology providers into the network to discuss how the supply chain could be realised and supported. The starting point would be the SAF demand analysis from the sector – how much, at what locations and over what timeframes. This extended group could discuss, understand and plan how this supply chain could be realised. This could be at a high level, while at the same time allowing bilateral commercial discussions to take place, independently of public agency involvement.
   The public sector is again key to facilitate and grow this network, using its existing knowledge of industrial players and their plans and providing a forum for discussions that can help shape future government strategy.
   Key outputs could be a high-level action plan and initial commercial discussions between different players in the supply chain.
3. **Elaborate Possible Scenarios for Supply Chain Development**
   Part of this work could be to consider what options there are for building the supply chain – recognising that if Scotland wants to maintain its aviation sector and decarbonise in a manner

that supports a just transition, then it will need to support the adoption of SAF. Broadly speaking there are three scenarios that could be discussed with stakeholders:

a. 'Full-steam ahead' – where there is strong public sector support for a Scottish SAF plant, that pulls in technology providers and a consortium of Scottish airports and airlines. This could be in the form of a competition, perhaps supported by investment from the Scottish National Investment Bank (SNIB).
b. 'Take it slow' – where the initial focus is on supporting the blending of (imported) SAF through tax incentives (perhaps funded by Air Passenger Duty Taxes) to reduce the cost of SAF to users and to build capability, capacity and demand across Scotland.
c. 'Wait and see' – where Scotland continues to implement green electricity, green hydrogen and CCUS plans, thus laying the foundations for a future SAF supply chain. Further development decisions would be made on the basis of the outcomes from the SAF demonstration plants in England and Wales.

While the investment risk from following option 'c' might be lower, we believe that the time lag would be too long to be confident that Scotland remains ahead of, or at least with the curve of global SAF developments. Option 'a', while potentially a significant investment and at a higher risk, would ensure Scotland's position in this transition. It could be de-risked through partnership with existing off-takers, and perhaps also through a modular plant approach. The efficiency of such plants could be improved through the involvement of other technology providers.

Scottish Government and the Enterprise Agencies can use this engagement to both highlight where existing strategies can support a Scottish SAF supply chain and to identify where there might be future opportunities to develop new interventions. Outcomes from this work may also be useful in discussions with the UK Government.

Key output could be a defined way forward that has support from the wider sector, and measurable outcomes.

4. **Demonstrate SAF Utility in a Scottish Context**

A modular plant approach could also be a way for the wider public sector, including Scottish Government, to consider the practicality of a distributed SAF supply chain, allowing for example, a number of hubs to develop (e.g. on islands and the mainland where there is sufficient access to renewable power and feedstock), while at the same time allowing scale-up to that required for supply to Scotland's larger airports serving international routes. There is strong potential for inward investment from technology companies to achieve this. However, given the narrow window of opportunity, this would need to allow the realisation of a larger scale plant (or plants) in the early 2030s to meet domestic demand expectations and export opportunities.

There could be an opportunity to use a combination of Scottish RTD funding, investment from SNIB and/or wider UK agency funding to support initial projects that are identified through the collaborative work of the network.

Key output could be an initial demonstrator project that provides confidence to the public sector and investors, for example, a full assessment and demonstration of a SAF-fuelled flight from the central belt to LHR, taking account of carbon footprint and other operational and logistics factors and costs. This could be perhaps similar to the Windracers project which showed what could be achieved with UAVs in terms of delivering mail and vital supplies from the mainland to island communities. This could be followed by demonstration of a modular plant, e.g., at RAF Lossiemouth, Grangemouth or St Fergus.

5. **Scotland as a Global Hub for SAF RTD**
   In parallel to the SAF plant development, there could be RTD support and coordination to demonstrate that Scotland offers a good environment to develop and optimise technology for SAF production, and the necessary support and opportunities to exploit this further and commercialise. This could involve indigenous companies, university groups and others, and could be a means of attracting inward investment, particularly if this is linked with demonstration facilities (e.g., the CCUS demonstrator plant that is planned at Grangemouth as part of the Falkirk Growth Deal) and other infrastructure being developed for green hydrogen and CCUS, e.g., as part of project Acorn.
   The activities and output delivered by the network and its associated activities, could be used by other agencies such as Scottish Development International (SDI) to engage with global stakeholders for the purpose of attracting inward investment.
   Key output could be a supportive RTD programme that helps position Scotland as one of the leading global locations for SAF technology innovation.

Further on, these investments could be used to better integrate all green hydrogen and captured carbon utilisation technologies with renewable electricity to support the creation of hubs that share these resources to develop and produce different products for multiple sectors. This could address multiple priorities in Scotland's Net Zero ambitions. SNIB will be a key asset for this to fund/support/guarantee the investment required for such SAF plants, while SDI's Green Investment Portfolio could market the opportunities for such projects.

The Scottish Government has the opportunity to be the driving force behind a SAF supply chain in Scotland and help create the best environment to achieve this. From industry's perspective what is needed is:

- acknowledgement of the importance of SAF to the decarbonisation of the aviation sector, including the support being delivered by the Enterprise Agencies to help develop a SAF supply chain in Scotland, and
- a strategy that sets out timelines and support from the Scottish Government to make this happen.

Delivering this would reassure the private sector of the commitment from the public sector to a Scottish SAF supply chain and provide a focal point around which this could grow.

This could also acknowledge the complex jigsaw of other net zero strategies in, for example, energy production, manufacturing, heating and other transport sectors with most, if not all, also making use of green hydrogen, CCUS, and green electricity. It could further highlight the connectivity between these different parts and the opportunities for complementarities and synergies. Ultimately, presenting such a strategy would further galvanise investment interest in Scotland.

APPENDICES

APPENDIX A – STAKEHOLDERS CONSULTED

Organisation	Organisation Type
ADS Scotland	stakeholder
Aerospace Defence Industry Leadership Group	stakeholder
Aerospace Technology Institute (ATI)	stakeholder
AGS Airports	stakeholder
Airbus	company
Argent Energy	company
Boeing	company
Bristow Helicopters	company
British Airways / IAG	company
Carbon Engineering	company
Cranfield University	academic
Drochaid Research	company
Edinburgh Airport	stakeholder
Fulcrum Bioenergy	company
Highlands and Islands Airports	stakeholder
IBioIC	stakeholder
iGTL Technology	company
Johnson Matthey	company
KTN	Stakeholder
Loganair	company
MB Aerospace	company
Net Zero Technology Centre	stakeholder
NMIS	academic
Nova Pangaea Technologies	company
Petroineos	company
RAF	stakeholder
Rolls Royce	company
Shell Aviation	company
SkyNRG	company
Sustainable Aviation	stakeholder
Sustainable Energies Scotland	company
Transport Scotland	stakeholder
UK Government's Department for Transport	stakeholder
University of Lancaster	academic
University of Sheffield - Sustainable Aviation Fuels Innovation Centre	academic
University of Strathclyde – Advanced Forming Research Centre	academic
Velocys	company

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