# Scaling SAF

**Scott Sayles, Pattabhi Raman Narayanan, and Jessica Hofmann, Becht,** consider technological pathways for sustainable aviation fuel (SAF) and its role in the road to net zero emissions by 2050.

The aviation sector faces significant challenges in achieving its goal of net zero carbon emissions by 2050. Sustainable aviation fuel (SAF) represents a critical component in this decarbonisation strategy, and offers a drop-in fuel alternative that can reduce lifecycle greenhouse gas emissions by up to 80% compared to conventional jet fuel. Despite its potential, the current global supply of SAF is insufficient, accounting for only 0.01% of total jet fuel demand. To meet the industry's sustainability targets, SAF production must scale dramatically, including setting a specification for the minimum concentration of renewable jet in fossil jet to qualify as SAF. However, the challenge of scaling SAF production is immense. To bridge the current gap between supply and demand, refineries will need to adopt new technological pathways, utilise a broader range of feedstocks, and navigate emerging certification and regulatory frameworks to ensure that SAF meets stringent sustainability criteria.

This article examines the key technological routes for producing SAF, including hydrogenated esters and fatty acids (HEFA), alcohol-to-jet (AtJ), gasification/Fischer-Tropsch (GFT), and power-to-liquid (PtL) processes, and the role refineries can play in scaling up these solutions. By exploring these opportunities and challenges, refineries can position themselves at the forefront of the aviation sector's sustainable future.

## Key technological pathways for SAF production

According to Annex 16, Volume IV of the International Civil Aviation Organization (ICAO), a SAF conversion process is defined as the technology used to convert a feedstock into aviation fuel. These processes are evaluated and approved by organisations like ASTM International to ensure their safety, sustainability, and compatibility with existing aviation systems.

As of July 2023, ASTM International has approved 11 SAF conversion processes, with another 11 currently under evaluation. To be used under ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), SAF must also meet strict sustainability criteria. Approved processes, including Fischer-Tropsch (FT), HEFA, synthesised iso-paraffins (SIP), and AtJ, have CORSIA default life cycle emission values, ensuring they provide substantial emissions reductions.

**Table 1.** **ASTM D7566 blend pathways**

| ASTM standard | Process name | Abbreviation | Feedstocks | Maximum blend ratio |
|---|---|---|---|---|
| D7566 Annex A1 | Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene | FT | Coal, natural gas, biomass | 50% |
| D7566 Annex A2 | Synthesised paraffinic kerosene from hydroprocessed esters and fatty acids | HEFA | Vegetable oils, animal fats, used cooking oils | 50% |
| D7566 Annex A3 | Synthesised iso-paraffins from hydroprocessed fermented sugars | SIP | Biomass for sugar production | 10% |
| D7566 Annex A4 | Synthesised kerosene with aromatics from non-petroleum sources | FT-SKA | Coal, natural gas, biomass | 50% |
| D7566 Annex A5 | Alcohol-to-Jet synthetic paraffinic kerosene | ATJ-SPK | Ethanol, isobutanol, isobutene from biomass | 50% |
| D7566 Annex A6 | Catalytic hydrothermolysis jet fuel | CHJ | Vegetable oils, animal fats, used cooking oils | 50% |
| D7566 Annex A7 | Synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids | HC-HEFA-SPK | Algae | 10% |

## Approved SAF conversion processes

ASTM D7566 defines the key conversion pathways and their blend limits with conventional jet fuel (Table 1).

The HEFA pathway was formally approved by ASTM in 2011. It involves the refining of vegetable oils, tallow, or waste greases into SAF through the deoxygenation and hydroprocessing of the feedstocks. It is the most mature of the SAF technologies and currently used today on a commercial scale.

AtJ using isobutanol as a feedstock, was approved in 2016, followed by the approval of ethanol as a feedstock in 2018. This pathway converts alcohol feedstocks like sugars, starches, hydrolysed cellulose, and industrial waste gases into SAF and other clean fuels, through several chemical processes.

GFT was the first SAF pathway to be approved by ASTM, in 2009. The process involves the conversion of a synthesis gas (syngas) into liquid fuel via a FT reaction. FT is a common commercial process for producing liquid fuels from both coal and natural gas. Syngas is produced from the gasification of cellulosic feedstocks or municipal solid waste. The syngas is then converted to a mixture of hydrocarbons, the main chemical component of jet-fuel in a FT reactor, before being further refined into SAF and other clean fuels.

PtL is another type of drop-in fuel produced using green hydrogen and sustainable carbon dioxide ($CO_2$). Like the advanced biofuel pathways, the PtL process can also be used to produce a series of clean fuels. PtL involves the conversion of syngas into SAF via a FT reaction. However, the syngas is produced from either green hydrogen and captured $CO_2$ via a reverse water-gas-shift reaction or directly via co-electrolysis using solid oxide electrolysis cells and clean electricity.

Process flow schemes for hydrotreating and hydrocracking are similar. Both use high-pressure hydrogen to catalytically remove contaminants from petroleum fractions. Both achieve at least some conversion, and they use the same kinds of hardware, whereas hydrotreating and hydrocracking differ in other ways. For a given amount of feed, hydrocrackers use more catalysts and operate at higher pressures. They also use different catalysts. Because they make large amounts of light products, hydrocracker fractionation sections must be more complex. In some hydrocrackers, unconverted oil from the fractionation section is recycled, either back to the front of the unit or to a separate cracking reactor.

## The impact of feedstocks on SAF scalability and sustainability

Types of feedstocks used for SAF include agricultural residues, municipal solid waste, dedicated energy crops, wet wastes, and renewable methanol.

Biofuels are divided into three categories: first generation, second generation, and third generation, from the least to most environmentally advantageous. SAF derived from biomass stands out as a leading contender for the aviation sector.

The primary sources of biomass-waste feedstocks are agricultural and forestry residues. Also, feedstocks such as lignocellulosic biomass, sugar beet, corn grain, sawdust, forest residue, wood residue, sugarcane bagasse, straw, agricultural wastes, and others have the characteristics for producing SAF from biowaste. In addition, the second generation feedstock sourced from animal fats, used cooking oil, and nonedible oil seeds have also been used for SAF. The pathway involves the conversion of lignocellulosic biomass and municipal solid waste into syngas by gasification followed by FT synthesis. Microalgae is also emerging as a prominent choice for a third generation feedstock due to their rapid growth rate. However, microalgae-based SAF faces challenges such as elevated production costs, intricacies in harvesting and processing, and difficulty to meet SAF standard specifications like fossil fuels.

Municipal waste is a cost-effective source but requires expensive pre-treatment. Used cooking oil is a low-cost, easily accessible feedstock, whereas straw is inedible but has higher alkali-metal content and transport costs. Energy crops such as Jatropha and algae offer rapid growth without competing with food crops, whereas wood waste is currently low-cost due to low local demand.

A lifecycle analysis is meant to capture the entire impact in terms of carbon emitted from the first point of origination to the last point of delivery. Comparing the life cycle analysis of SAF to fossil derived jet fuel demonstrates the major net carbon benefit of SAF. A typical blended SAF with fossil derived fuel achieves a 20 - 25% reduction in emissions, with variations depending on the feedstock and blend. A lifecycle analysis is conducted to draw these comparisons, determining the final environmental footprint of a given batch. It is important to note that not all SAF is the same.

## The emergence of e-fuels

E-fuel is a liquid fuel made from water and carbon dioxide in a PtL process powered by renewable energy. Hydrogen, produced via water electrolysis using renewable energy, reacts with captured $CO_2$ using innovative technologies to make e-fuel. The use of renewable power and capturing $CO_2$ from the atmosphere makes it a carbon-neutral fuel when it is burned, producing no net greenhouse gas (GHG) emissions.

Unlike other SAF pathways that rely on biological feedstocks, e-SAF is a groundbreaking synthetic fuel that requires green hydrogen and $CO_2$ (biogenic or non-biogenic) to offer a clean, low-carbon alternative to fossil-based jet fuels.

## Role of e-fuels in reducing carbon intensity

E-fuel is gaining momentum as a way of reducing carbon footprints in the transportation sector, which accounts for around a fifth of global energy-related $CO_2$ emissions. At present, e-fuel is more expensive than conventional fossil fuels. Japanese automakers are eyeing e-fuel as an alternative to EVs. They believe e-fuel has an edge over biofuel as biofuel production runs the risk of destroying forests and ecosystems, especially in developing countries. E-fuel will also lead to the sustained use of advanced technology within internal combustion engines and existing infrastructure such as pipelines and gas stations.

## Potential for e-fuels to complement SAF in the aviation sector

In 2023, Norwegian and Norsk e-fuel signed a strategic partnership agreement to build the world's first large scale production facility for electrofuel in Mosjøen, northern Norway. Electrofuel, often called e-fuel, is a fossil-free aviation fuel that can be used in today's aircraft. Norsk e-Fuel is starting the industrialisation of e-fuel production in Mosjøen, Norway, and will start to provide e-fuels to the aviation industry after 2026. Backed by a strong shareholder and partner network, the company looks to increasing production with two additional plants by 2030.

The passenger airline Norwegian and the cargo airline Cargolux have committed to the offtake of e-SAF of more than 140 000 t of fuel supply. In addition, the two companies will provide strategic support for the development of two additional production facilities by 2030.

## Certification and regulatory challenges

Navigating international standards is crucial for the global adoption of SAF. The path to widespread SAF adoption faces regulatory challenges that can slow down progress due to multi-stage certification and approval processes that can be lengthy and resource-intensive. The differences in regulatory requirements between countries can also complicate approvals.

The International Air Transport Association (IATA) states that SAF must demonstrate a net carbon reduction through a lifecycle analysis (LCA), which is an essential element of sustainability certification. Drop-in SAFs are also typically blended with conventional fossil derived jet. However, the international specifications for jet fuel developed by the ASTM aim to ensure that this is achieved safely and effectively, with current specifications allowing for a maximum of 50% SAF, depending on the SAF type used for commercial flights (compared in Table 1).

There are significant regulatory challenges to increasing the supply of SAF. These include evolving the certification and approvals process for new production pathways whilst maintaining safety and monitoring feedstock standards to ensure sustainable practices.

## Scaling-up SAF production

The success of SAF scaling hinges on strategic partnerships, targeted technology deployment, supportive regulations, and financing mechanisms. Global collaboration, investment, and supportive policies are needed to bridge the projected demand-supply gap in 2030 and beyond.

The most significant economic barrier is that SAF is currently approximately two to five times more expensive than traditional fuel costs and requires favourable tax and subsidy policies to become feasible for airlines to use in the short-term. Innovation by start-ups and incumbents are helping to bridge the gap between SAF technologies and commercially viable pathways.

There is currently a lot of attention on newer technologies like PtL, which removes the feedstock-related barriers by only using water, renewable energy, and $CO_2$ as inputs. However, HEFA is still the most mature SAF production technology today. Across North America there is a significant amount of announced HEFA production, with a proportion of AtJ which mostly comes from corn starch.

As an industry, it is possible to draw on experience in other renewables, where costs have decreased as these industries deploy. As the SAF industry develops, so too will additional feedstocks and pathways.

SAF supply chains will involve engagement with and contributions from a diverse group of stakeholders as coalitions provide a functional platform for collaboration and engagement among a diverse set of supply chain participants. Strong public-private SAF collaborations help mitigate risks for all parties; aid in establishing a secure, stable, and competitive SAF supply chain; and help establish long-term competitiveness of SAF.

SAF needs rapid technology adoption, and net zero corridors that connect global production hubs to demand centres. Also crucial are collaboration, regulation, incentives, and accounting standards.

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