Executive summary

by Glen O’Kelly

The market for sustainable aviation fuel (SAF) is at a critical juncture, as recently proposed regulations in the EU and proposed legislation in the US appear likely to drive rapid growth in the coming years from its current, and very small, footprint. We expect global SAF demand to grow from its present size of about 80,000 tonnes to almost 3 million tonnes by 2025. This is enormous growth but from a relatively low base. It requires SAF production to more than double every year and reach a level 30-35 times larger in 2025 than it is currently.

This presents an enormous opportunity for many market participants, including SAF producers, investors and raw materials suppliers. But the growth of the SAF market also presents many challenges that will need to be overcome, such as sourcing sufficient – and genuinely sustainable – raw materials, financing the construction of the required SAF facilities and developing adequate infrastructure for the delivery of SAF to the aviation sector. Reducing the production costs of SAF will also be critical to narrow the cost gap with conventional aviation fuel and at the same time reduce the burden on governments and consumers.

In this study, we first examine the drivers of SAF demand and present a forecast for demand to 2025. After that, we discuss the various pathways for the production of SAF, including raw materials requirements and opportunities for cost reduction. The third chapter considers raw material requirements and their potential availability, including a deep dive into the markets for used cooking oil (UCO), virgin vegetable oils (VVO) and forest-based residues, as well as sustainability considerations in sourcing SAF. We then provide a view on expected supply development and the leading SAF producers that are driving this expansion, before closing the report with our perspectives on the main hurdles for the successful growth of SAF adoption, and scenarios for how the SAF market is likely to develop in the next five years.

Demand drivers

The underlying driver for all SAF demand is efforts by airlines, consumers and regulators to reduce greenhouse gas (GHG) emissions from aviation. While aviation emissions are relatively small, at about 2% of total GHG emissions, they are growing rapidly with the increased demand for air travel and slow improvements in energy efficiency. Global GHG emissions from aviation doubled between 1990 and 2019 and could increase four-fold by 2050 if steps are not taken to decarbonize. But aviation is one of the most challenging sectors of the economy to decarbonize. Due to the weight requirements on aircraft, they need an energy source with very high energy to weight and volume ratio (energy density). Aviation also has very strict safety requirements. While road and marine transport are starting to shift to low-carbon technologies such as electric battery and hydrogen fuel cells, these technologies are still not viable alternatives for most aviation. As electric battery and hydrogen technology develops, they are expected to slowly be deployed in aviation, starting with the shortest-haul flights, but even by 2050 all long-haul flights are expected to require aviation fuel (conventional kerosene and/or SAF).

While global air travel fell sharply in 2020 (by 35% versus 2019) and is still lower than usual in 2021, it is expected to recover strongly in 2022 and 2023, regaining pre-pandemic levels by 2024. Much of that growth will be driven by Asia and other emerging economies, as increasing numbers of consumers are able to afford air travel. We expect 6% annual growth in air travel from 2024. Meanwhile, fuel efficiency is expected to improve only gradually, by around 1% per year, via more efficient engines, aircraft design and airline operations. Demand for aviation fuel will therefore increase at around 5-6% per year from 2024.

The most important factor that will determine SAF demand in coming years is the rate at which it replaces conventional (fossil) aviation fuel. SAF is currently less than 0.05%

of total aviation fuel demand, and is mainly used in the few countries which have already introduced SAF blending mandates, such as Norway. Many aviation groups and airlines have also voluntarily committed to using a certain share of SAF in their aircraft, such as Airlines for America (A4A), a trade association of leading US airlines, Scandinavian Airlines and Amazon Air, the cargo airline for the internet retailer. With rising public concern for aviation emissions, demonstrated in consumer surveys and new cultural expressions such as "flight shame", there is increasing pressure on airlines from consumers and investors to reduce the environmental impact of their flights. But the most powerful driver for the increased adoption of SAF in the next five years will be government regulations.

Two regions are expected to lead in SAF adoption, driven mainly by government regulation: the European Union and the United States. In July 2021, while this study was being finalized, the European Commission published a proposal for a new regulation, ReFuelEU Aviation, that involves steadily increasing SAF blending mandates of 2% in 2025, 5% by 2030, 20% in 2035, 32% in 2040 and 63% by 2050. This is more aggressive than some country-level mandates for 2025, for those countries that have one (Chapter 1 Figure 10), and establishes a continent-wide minimum level that covers those countries that have not yet drawn up a national mandate. The Commission also published a proposal to include a minimum tax rate on conventional jet fuel, which is currently exempt from any tax. Meanwhile, in the US, two acts designed to increase the use of SAF have been introduced to Congress, the Sustainable Aviation Fuels Act and the Sustainable Skies Act. Both would introduce a blender's tax credit for SAF – up to US$1.70 per gallon in the former and up to US$2.00 per gallon in the latter – which would be enough to close the gap between conventional kerosene and the lowest-cost SAF. It remains unclear whether this legislation will be passed, especially in the Senate. While the hurdles for introducing a national blending mandate are high, our view is that there are strong chances that the federal tax credit will be implemented. In our SAF demand forecast for 2025, we assume a SAF share of total aviation demand of 2% in Europe and 1% in North America. In Asia Pacific, the region with almost 40% of global aviation and the fastest growth, we assume only a 0.1% SAF share – for now, we do not see enough regulatory support in the region for any significant level of SAF adoption. But that could change quickly and is one source of uncertainty in our forecast. In the past, China has shown an ability to quickly implement renewable energy policies if these are considered a national priority.

Technology and cost

SAF production technology is still very new and under development. There are currently only a handful of companies that manufacture SAF on a commercial scale. Efforts to improve SAF production technology are focused mainly on reducing production costs while also ensuring the SAF is compatible with existing aircraft engines and at least as safe as conventional fuels.

SAF is intended to be a drop-in fuel, meaning that it has chemical and physical properties almost identical to conventional jet fuel and the two can be easily substituted at varying degrees. Currently, the standardization for SAF offers a maximum blending ratio of 50% to be used in commercial flights, but test flights are also being made with 100% SAF. There are currently four main SAF production pathways. While there is no significant difference in the properties of the SAF produced by each method, they do differ in the production process, the feedstocks that can be used, and the operating and capital costs associated with the facilities.

1. **Hydroprocessed esters and fatty acids (HEFA).** This pathway is by far the most common. We estimate that 100% of SAF produced today and until 2022 will be using the HEFA process, and it will account for over 80% of the production volumes through 2025. The process is linked to the well-established hydrotreated vegetable oil (HVO) production of road diesel, and mainly uses oil or fat feedstocks such as used cooking oil (UCO), vegetable and animal oils, animal fats, tall oil and palm fatty acid distillate (PFAD). The pathway is the most cost competitive of the SAF pathways, but the relatively narrow choice of feedstocks are a significant disadvantage.

2. **Gasification/Fischer-Tropsch (G/F-T).** This pathway is currently the most cost competitive after HEFA but remains in pilot phase for commercial production of SAF, and we expect it to account for less than 10% of production through 2025. The technology is not new and feedstock requirements are relatively broad, including lignocellulosic materials (e.g., wood, straw), solid municipal waste and industrial waste gases. While raw material costs can be low, the process has very high capital costs because of the equipment required for gasification and gas treatment.

3. **Alcohol-to-jet (AtJ).** AtJ can also be based on relatively broad range of feedstocks, including sugar and starch crops as well as lignocellulosic materials, but the conversion yield to SAF is low (around 13%). The process begins by fermenting the feedstock to produce alcohol, which is then further processed to make alkenes and then biofuels. The process is well established, but making AtJ from second-generation (non-food) feedstocks is less common, and production of SAF from alcohol is still under development. We expect it to account for less than 10% of SAF production through 2025.

4. **Power-to-liquid (PtL).** The clear advantage of the PtL pathway is that the two feedstocks required, carbon dioxide and water, are plentiful. The process first uses hydrolysis to produce hydrogen, which with carbon dioxide is then processed into fuel using the Fischer-Tropsch process. The challenge with PtL is that it is by far the most expensive process for SAF production, due to the renewable electricity required for the hydrolysis of water to hydrogen and the capital costs of the facilities. We do not expect significant production of PtL by 2025, but in the long term it is in many respects the most promising of all SAF pathways.

Production costs for SAF are expected to fall steadily with technological advancements, increased scale and the "learning curve" of manufacturers. The goal is to close the gap as much as possible between the cost of SAF and conventional aviation fuel, which is currently priced at around US$600-700 per tonne. The HEFA process is the closest, with current costs of US$1,150-1,650 per tonne that are expected to fall to US$750-1,500 per tonne by 2050 through improvements in conversion yield and capital costs. The G/F-T pathway is higher cost but expected to see greater cost compression, from a current range of US$1,300-2,400 per tonne to US$1,150-1,750 per tonne by 2050. That improvement will be achieved mainly through the reduction of the large capital costs. AtJ will remain relatively high cost but will see some cost compression through lower ethanol and renewable hydrogen production costs, dropping from a current range of US$2,100-3,000 per tonne to US$1,400-2,300 per tonne by 2050. Finally, PtL costs will fall the most but are still expected to be higher than for any other SAF, except perhaps AtJ, well past 2030 – falling from a current US$1,500-5,000 per tonne to US$1,000-2,300 per tonne by 2050.

Raw materials

The expected rapid growth in SAF demand, and production, will require the mobilization of raw materials. The volume of raw materials required by 2025 is relatively modest compared to the potential supply, current use by other sectors (such as road biofuels) and the volume required if SAF production continues to grow as anticipated through 2050. Still, sourcing adequate raw material will be a critical challenge for SAF producers. The principal challenges include setting up supply chains for raw material supply where they do not currently exist, sourcing at prices low enough to remain cost competitive, and ensuring the sustainability of raw material production and the supply chain.

Given that all commercial SAF facilities currently use the HEFA pathway, the most commonly used feedstocks at present are various forms of lipids, such as UCO and VVO. We expect the dominance of HEFA and its reliance on these feedstocks to continue through 2025. Based on announced SAF capacity expansion, we estimate that about 80% of the feedstock used in 2025 will be oils and fats – around 60% UCO, 15% palm fatty acid distillates (PFADs) and 5% VVO. The remaining feedstocks will be crop residues (~10%), forest residues (~5%) and municipal solid waste (~5%).

The theoretical supply potential of these feedstocks is many times larger than the requirement by 2025, and well beyond. Using data from within Fastmarkets in addition to figures in a recent study on SAF by the World Economic Forum,[1] we estimate a supply potential of well over 3 billion tonnes of materials that are suitable for SAF production, while expected SAF production in 2025 would require around 6 million tonnes. Oil and fat feedstocks such as UCO are relatively more constrained, but even these materials have a much larger supply potential than currently utilized. And the use of non-HEFA pathways for SAF production opens up the opportunity to use feedstocks that are far more abundant, such as agriculture and forest residues.

The sustainability of various raw materials is a critical question for SAF producers. Two important considerations are the GHG emissions savings achieved with SAF manufactured from a particular feedstock, and the sustainability of the feedstock production process and its supply chain, including ecological and social considerations. There is a general push for the biofuels industry to transition from first-generation feedstocks, such as edible oils and sugar crops (e.g., soybean oil, sunflower oil, sugar cane and maize) to advanced and waste feedstocks. The latter includes waste products such as UCO, agriculture and forest residues, as well as non-edible and purpose-grown crops such as cellulose cover crops and oil trees. SAF buyers are increasingly relying on independent certification of the sustainability of SAF products. The Roundtable on Sustainable Biomaterials (RSB) is the leading body providing sustainability certification for SAF. The RSB applies the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) standard recognized by the International Civil Aviation Organization (ICAO) to certify the sustainability of various feedstocks.

Each feedstock presents a unique set of advantages and disadvantages, and in this study, we examined the market development for three feedstocks more closely: UCO, VVO and forest feedstocks. UCO will remain the go-to feedstock for most SAF producers through 2025. While it is used for many things, including plastics, paints and biofuels, most UCO is still not recycled. Prices for UCO rose sharply in 2021 with increased demand for the production of biofuels. Global trade has also grown rapidly, with Europe importing UCO from China and the US. Increasing UCO-based SAF production will also put upward pressure on UCO prices. The evolution of UCO prices in the coming years will depend largely on how successful the biofuel and SAF industries are in unlocking currently unutilized volumes. China has emerged as a large UCO exporter, selling UCO that was until recently commonly dumped in waste-water systems.

Virgin vegetable oils are highly suitable for SAF production but also controversial. Palm oil plantations in Southeast Asia and soybean plantations in Latin America have been linked to deforestation. Reliable sustainability certification and development of novel crops will be critical for these feedstocks to be widely used in SAF production. But in many regions, virgin vegetable oils will be an important feedstock for SAF. The US Department of Agriculture (USDA) predicts that an increasing share of soybean production will be used to make biofuels. Research is also being done on novel crops, such as carinata, an inedible oilseed crop suitable as a winter crop between main summer crops. Sugar cane, an edible sugar crop that has many similarities with virgin vegetable oils, is highly suitable for AtJ production and well established in Brazil for ethanol production. Other leading sugar producers, such as South Africa, are increasingly interested in using sugar cane to make biofuels, including SAF.

Forest feedstocks include a wide range of materials; some of these are highly prized raw materials for the forest industries, but others are largely unutilized today. Most residues from forest industries, such as sawmill chips, sawdust and pulping byproducts, will continue to be used within the industry as raw material or a source of energy. The most promising forest feedstock for SAF producers is waste generated in forestry operations: branches and tops, stemwood offcuts and stumps remaining after harvest. In most regions, these are not utilized, and even in Scandinavia, where forest residue supply chains are well established, only a fraction of the potential is utilized.

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[1] *Clean Skies for Tomorrow*, November 2020.

Supply development

Current global SAF capacity is about 300,000 tonnes. Based on announced capacity expansion projects, and interviews with project owners, we expect capacity to quickly expand to around 3.3 million tonnes by 2025. Of this additional 3.0 million tonnes of capacity, about 1.1 million tonnes will be from projects already under construction, 1.6 million tonnes from projects that are still in the planning phase, and 300,000 tonnes from existing biofuel facilities ramping up production and/or converting to SAF. This is more than sufficient capacity to meet forecasted demand of 2.7 million tonnes by 2025. And there is, in our opinion, little risk of overcapacity because projects will inevitably take time to ramp up to full capacity and demand is growing rapidly; at expected growth rates, demand will be in excess of 6 million tonnes by 2026.

Almost all expected capacity in 2025 will use the HEFA pathway, with only relatively small volumes of G/F-T, AtJ and PtL. All of the largest four producers by expected capacity in 2025 will be using the HEFA process: Neste, World Energy, Total SE and NEXT. The only large producers planning to use other pathways are Gevo and LanzaTech (AtJ), Fulcrum and Red Rock (G/F-T). As discussed earlier, this will have implications for raw materials, with the greatest demand expected for lipid feedstocks such as UCO and VVO.

There are a few uncertainties surrounding the supply outlook. The first is regulatory support; many of these projects will not go ahead as planned unless the EU and the US implement the proposed legislation to drive SAF demand and help close the cost gap between SAF and kerosene. Another is project financing, because SAF projects are inherently risky, given that this is a new and rapidly evolving market using technology which is still under development and largely unproven at scale. These risks need to be mitigated by project owners, with support from regulators, for projects to attract the financing required. Finally, there is uncertainty around the degree to which existing biofuel facilities will shift production from the road and marine sector to SAF. Technically, facilities can switch, for example, from producing HVO road diesel to HEFA, but for producers to do so will depend largely on the relative support that regulators give to SAF versus other biofuels and how competing biofuel industries react. We expect policy to favor the production of SAF over road and marine biofuels because there are fewer sustainable alternative technologies currently available for aviation.

Market outlook

How exactly the global SAF market will evolve in the next five years is too early to say. In our forecast, we map out three broad scenarios. In the base case, which we consider most likely, the EU and the US introduce legislation to support the use of SAF, through blending mandates (EU) and tax rebates (US), but no other jurisdictions of significant size do so by 2025 (except for national-level commitments already made). Airlines implement their voluntary commitments to SAF, and SAF penetration reaches about 0.8% of aviation fuel demand. Currently announced capacity projects will be sufficient to meet this demand, including some repurposing of road biofuel facilities to SAF. Rapid scale-up of SAF production will help deliver the roughly 1% per year cost reduction we project for most pathways. Growing pains will be felt in some feedstocks and regions, as SAF producers and raw material suppliers scramble to establish efficient supply chains, including collection, production and transport.

It is also possible that SAF adoption will be slower than our base case, attaining only about a 0.1% share of aviation fuel globally by 2025. This scenario is likely if the US does not adopt the proposed tax rebates and the EU cancels plans for the SAF blending mandate or introduces a far less ambitious program. Demand would be driven mainly by already implemented or announced national blending targets and voluntary commitments by airlines.

In a more optimistic scenario, SAF penetration could reach well over 2% of the aviation fuel market. This could result if the EU and the US implement regulations to either enforce or incentivize the use of SAF, as well as one or two large countries in Asia, particularly China or Japan, although we consider this unlikely before 2025.

There are a few key factors that will determine how the SAF markets evolve.

These are also important considerations for policy makers, producers, buyers and other market participants to ensure a positive development of the SAF market.

- **Regulatory support.** Governments have a critical role to play, not only in incentivizing airlines to use SAF despite the significant cost premium over conventional aviation fuel (e.g., through mandates, subsidies and tax rebates), but also in establishing fuel standards, supporting research and assisting with financing of SAF projects and the necessary infrastructure.

- **Airline commitment.** Airlines clearly need to be on board in the transition to SAF, because they are usually the key decision makers in the selection of aviation fuel. Even if government support helps remove or mitigate some of the economic barriers to SAF adoption, strong commitment from airlines will be required to enable the transition.

- **Consumer demand**. For the most part, consumers will not be aware of what SAF blend is used on a given flight. The price of air travel will rise slightly in regions where mandates are introduced, such as Europe. For SAF adoption to succeed, it is necessary that there is not a consumer backlash. Fortunately, consumer surveys indicate strong support for more sustainable aviation. In regions without government intervention, consumer demand for SAF flights might be an important driver.

- **Raw material supply.** We do not see a physical shortage of raw materials for SAF manufacture, certainly not by 2025 and probably not for the foreseeable future. But each SAF facility will have a unique set of challenges in sourcing raw materials in their location, often requiring establishing entirely new supply chains. Price volatility in some feedstocks is likely, as seen recently with UCO and soybean oil, as rapid growth in demand for these materials must be met with new supply.

- **Production costs**. The cheapest SAF currently, produced via the HEFA pathway, still costs two to three times more than fossil kerosene. The additional cost needs to be covered by higher prices for air travel or government support. We expect that both consumers and governments have limits to how much and for how long they will fund the adoption of SAF. Therefore, it is essential that SAF production costs are quickly reduced though research, producer "learning curves" and operational improvements, and the up-scaling of facilities.

- **Project financing**. New SAF facilities typically cost US$2,000-3,000 per tonne of capacity, and to meet expected demand in 2025, an investment of over US$7 billion will be required over the coming three to four years. This is larger than the investment in all biofuels in both 2019 and 2020 – but smaller than the investment in biofuel capacity in the boom years (e.g., 2010) and only a fraction of the current investment in solar and wind power. To attract financing to this sector, it is critical to de-risk projects, for example, through partnerships between SAF producers, airlines and energy companies, and secure future demand through offset agreements. Governments can also help de-risk through clear and stable regulations and support and by assisting project financing through guaranteed loans.