Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF):

Technologies and policies

IEA Bioenergy Task 39

January 2024



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Susan van Dyk and Jack Saddler

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Executive Summary

In 2022, the aviation sector's commitment to mitigating its climate impacts was indicated at a global level by the International Civil Aviation Organization (ICAO), setting a net zero target by 2050. ICAO's long-term aspirational goals (LTAG) report describes the measures that will be taken to reduce the sector's climate impact. This follows the separate target in 2021 of net zero by 2050 as agreed by the International Air Transport Association (IATA). Both documents agreed that a basket of measures would be required to meet the net zero target, including new technologies, improved operations, sustainable aviation fuels, carbon offsets, etc. However, according to IATA, 62% of emissions reductions must come from using sustainable aviation fuels.[1]

More recently, the non-CO2 impacts of aviation have also gained attention, and it has been suggested it could account for a significant part of the sector's total climate impact. For example, the aromatic content of jet fuel and specific types of aromatics have been identified as contributing to the non-CO2 effects. Although sustainable aviation fuels can play a role in reducing these impacts (using fuels with reduced or zero aromatics), this needs to involve modifying jet fuel standards such as ASTM D1655 and ASTM D7566.

Since the last IEA Bioenergy Task 39 biojet/SAF report in 2021, the production and use of SAF have grown substantially. In addition to the increasing availability of SAF, the number of new facilities that have been announced and are under construction should result in an exponential increase in SAF production by 2030. This has been partially driven by SAF-specific policies in jurisdictions such as the EU (the ReFuelEU Aviation mandate) and the USA (the Inflation Reduction Act (IRA) and state-specific SAF tax credits).

For example, the ReFuelEU policy has targeted aggressive blending mandates with a specific sub-mandate for efuels. It has been suggested that the long-term certainty of mandates should reduce risk for investors while creating a level playing field for all airlines. However, the RefuelEU Aviation policy did not include incentives that would bridge the price gap between conventional jet fuel and SAF. In contrast, US policies will primarily rely on incentives to promote the commercialization of SAF. These substantial SAF blender tax credits (for two years), followed by SAF producer tax credits (for three years), should promote the consumption of available SAF based on the fully commercial HEFA process while incentivizing the development of near-commercial technologies and boosting the construction of biorefineries in the US. Hopefully, the higher incentives for SAF compared to renewable diesel will

[1] https://www.iata.org/en/pressroom/2023-releases/2023-06-04-03/

address the competition between aviation and road transportation. In parallel, the "stacking" of IRA incentives with the Renewable Fuel Standard (RFS) RIN credits, as well as state-level SAF credits introduced in Illinois, Washington, and Minnesota, should make SAF production and consumption a very attractive financial proposition for investors and consumers.

As covered in more detail within the report, there has been significant progress in the commercialization of technologies accompanied by considerable investment in research and development. As there are specific challenges associated with various pathways, the lipid-derived HEFA-pathway will continue to supply the majority of SAF volumes up to 2030. However, alternative technologies, such as gasification with Fischer-Tropsch and alcohol-to-jet, are nearing commercial status. Although several companies are pursuing the power-to-liquids technology for efuels SAF production, this pathway is at a lower technology readiness level, with components of this technology, such as the reverse water gas shift reaction, still needing to be fully resolved.

In keeping with past reports, a dominant focus of this report is on technologies, key developments in commercialization and recent research-and-development trends. These aspects are addressed in great detail in previous reports, such as the 2014 drop-in report, the 2018 update (with a focus on coprocessing), the 2021 report (on biojet/SAF commercialization), and the 2022 report (on updates in coprocessing). This current report builds on these previous reports, which can be consulted for background.

Trends and challenges of the lipid-derived-HEFA pathway

Although the HEFA pathway has been fully commercial for some time, it has been primarily used to produce renewable diesel rather than SAF. However, a substantial number of new facilities based on this technology will target SAF production by diverting a fraction of the total liquid product to SAF (up to 70%). Although a relatively small fraction (~15%) of hydrotreated fats and oils fall within the jet range, this can be increased, but at a higher cost and with a loss of overall liquid yield. The development of new isomerization catalysts that can increase the SAF fraction and minimize loss of yield is a new trend that has been reported for this pathway. However, the decision to shift to increased SAF production will likely be based on financial considerations, with policy playing a key role, as SAF must compete with renewable diesel for road transportation.

The availability of waste/lower carbon Intensity (CI) feedstocks (e.g. Fats, Oils and Greases, (FOGs)) will soon limit the production of bio/renewable diesel and SAF via the HEFA pathway as crop-derived lipids

typically come at a higher CI or may have other sustainability challenges. While alternative oilseed crops (e.g., Carinata, Camelina) could potentially provide additional sustainable feedstock volumes, commercial availability is currently insignificant.

With an increasing focus on low-quality waste feedstocks that contain numerous contaminants, on-site and optimized pretreatment technologies are receiving more attention. In addition, new technologies are being developed for licensing, which reduce yield losses while achieving the refinery's quality specifications.

Trends and challenges of gasification-based technologies for SAF production

Gasification of biomass produces syngas that can be used in multiple pathways to produce SAF. Syngas can be used for SAF production via Fischer-Tropsch synthesis or via a methanol intermediate and methanol-to-jet conversion. Alternatively, the syngas can be fermented to ethanol, with the alcohols converted into SAF via the alcohol-to-jet pathway. Multiple projects that use these different pathways have been announced. Regardless of the downstream use of the syngas, syngas cleanup remains a critical component of this pathway to prevent downstream catalyst deactivation.

Fischer-Tropsch synthesis can achieve direct conversion of biomass to hydrocarbons, which contain a jet fraction. In the conventional FT-process, using Fe or Co as catalysts, the product distribution obeys the Anderson-Schulz-Flory (ASF) statistical model with the maximum straight-run jet fraction limited to about 40%. Although multiple, additional process units can be used to increase the SAF fraction through hydrocracking, alkylation, etc., this is achieved at an additional cost. However, early-stage research and development is currently targeting the development of catalysts that have a higher selectivity towards the jet fraction based on a statistical distribution that does not obey the ASF model. Although these bifunctional catalysts show great promise, they will require independent ASTM approval as, currently, ASTM D7566 Annex 1-approved SAF is limited to Fe and Co catalysts.

The first small-scale commercial facility using gasification with Fischer-Tropsch synthesis, Fulcrum Bioenergy, commenced operation in 2022, and municipal solid waste is used as the feedstock. Although the company successfully produced FT liquids (syncrude) that were sent to the Marathon Petroleum Refinery for co-processing, it is not clear whether any substantial amounts of SAF have been produced via this process. FT liquids are approved under ASTM D1655 for co-processing at a maximum of 5% blends.

It should also be noted that the gasification process is designed around the specific feedstock used, which impacts the feedstock preparation, type of gasification reactor and the syngas cleanup process. While the Fischer-Tropsch process is fully commercial, the preceding processing steps, as well as the overall integration of the process, have yet to be fully commercialized. Several other gasification-based facilities are planned or under construction in North America and Europe by companies such as Velocys, DG Fuels, Enerkem, and Fulcrum Bioenergy. However, the high investment required for gasification-based facilities and the lengthy construction process will likely result in a slow ramp-up of commercial volumes via this pathway.

As mentioned earlier, although multiple biomass feedstocks can be used by gasification-based technologies, including MSW and forest and agricultural residues, supply chains for these types of feedstocks are not well-established. For example, the low energy density of forest residues limits the economical transportation distance from a refinery, impacting the scale of refineries. Unless supply chains are developed with intermediate densification (e.g. pellets or bio-oils), large-scale facilities will be difficult to establish. Although several companies have announced very large-scale projects in this area, it is not clear how the energy-density challenges will be overcome while keeping feedstock costs within a reasonable margin. Although there is also no lack of availability of agricultural residues, factors such as a higher ash content, lower density, seasonality, etc., will likely present different challenges at the refinery. Supply chain issues for agricultural residues have played a significant role in the lack of success of cellulosic ethanol, and the same challenges are expected for gasification-based pathways using this feedstock.

Trends and challenges of the Alcohol-to-Jet (AtJ) pathway for SAF production

The first small-scale commercial AtJ facility, Lanzajet's Freedom Pines facility in Georgia, is expected to be completed and commissioned in early 2024. Multiple other facilities based on the AtJ technology are planned across the globe, and several companies are offering integrated technologies that could be licensed. Various types of alcohols can be used for SAF production, with ethanol and isobutanol already approved under ASTM D7566. The Swedish biofuels AtJ process uses C2-C5 alcohols and achieved ASTM approval in August 2023. Furthermore, the methanol-to-jet pathway is in the pipeline for ASTM approval. While Gevo spearheaded the production of isobutanol as the starting alcohol for their isobutanol-to-jet pathway, this company is currently pursuing commercial production based on ethanol as the feedstock alcohol. Although the majority of announced facilities will be based on ethanol-to-jet, they will differ in their approaches to ethanol production or supply. Some companies plan to purchase

ethanol, while others plan to integrate ethanol production with the AtJ process. Several companies plan to produce ethanol via Lanzatech's syngas fermentation process, while others are targeting cellulosic ethanol production.

Fairly recent SAF reports (Blanshard et al., 2021; McKinsey & Company, 2020) do not include ethanol from corn, sugarcane or other types of crops in feedstock availability estimates, and only cellulosic ethanol is addressed, even though only a small amount of ethanol is globally produced from these cellulosic feedstocks. While companies such as Raizen and Praj are pursuing the commercialization of cellulosic ethanol, a long history of cellulosic ethanol company closures (most recently the Clariant facility in Romania) suggests that cellulosic ethanol for SAF production will be very limited in the near future.

Although there is an ongoing debate around corn ethanol and its carbon intensity, sugarcane ethanol has been shown to have a very low carbon intensity (CI) and will likely be a target feedstock for SAF production (while cellulosic ethanol develops). For the case of cellulosic ethanol via gas fermentation or alternative pathways, a major challenge will be the cost of the ethanol and, therefore, the cost of the SAF.

Trends and challenges of the Power-to-liquids (PtL) pathway for SAF production

The PtL pathway is considered a sustainable route for producing SAF as it does not require any biomass feedstocks. While it can achieve low carbon intensity SAF, this will be highly dependent on the source of electricity used for hydrogen production and the source of CO2. The high cost of production for PtL pathways will also present a major challenge. While several companies are commercialising PtL technologies, most of them are located in Europe, arguably driven by the ReFuelEU policy that establishes a dedicated sub-target for SAF volumes via this route.

Like the gasification pathway, the PtL process can use Fischer-Tropsch synthesis to directly produce hydrocarbons, or methanol can be produced and converted into SAF via the AtJ pathway. Although individual process steps are at different TRL levels (e.g. FT at TRL 9), the TRL for the overall integrated process is at the Reverse Water Gas Shift Reaction (RWGS) level, which is at about TRL 6. The RWGS reaction converts captured CO2 into CO to produce syngas for the downstream process and is a critical component of this pathway. While direct CO2 utilization is under investigation, it is at an early stage of development. An alternative to using the RWGS is co-electrolysis which is offered by Solid Oxide Electrolyzer Cell (SOEC) technology. However, this is also at early TRL levels, with Sunfire having just

completed a pilot plant based on SOEC hydrogen production. Thus, substantial technology development still has to occur for the PtL pathway to achieve commercial status. A significant consideration for the PtL pathway is the high cost of production, which is far higher than SAF technologies based on HEFA and ATJ, with some of the major cost contributors being the CAPEX for electrolysers and the cost of electricity for hydrogen production.

While the "feedstock" for PtL is considered unlimited by some, the reality is that PtL is only truly sustainable if "additional" renewable electricity is used. Thus, the availability of cheap, renewable electricity is challenging. As renewable electricity will be increasingly required for the decarbonization of heat and power and for supplying electric vehicles, the production of PtL fuels comes into direct competition with these applications. As the PtL pathway has a low energy efficiency due to energy losses along the conversion pathway, it has been suggested that these sectors should be decarbonized first before electricity is diverted to PtL production.

Co-processing to produce lower carbon-intensive (CI) jet fuels

During 2022/23, about six refineries in Europe started producing lower carbon-intensive jet fuels through co-processing, and further plans for refinery co-processing (to produce lower CI fuels) were announced by another seven refineries. Refinery co-processing is based on the insertion of 5% lipids in the hydrotreater, as this is the maximum fraction allowed by ASTM D1655. However, a subcommittee led by BP is currently spearheading the increase of the ASTM blend limit to 30%, which should potentially increase lower carbon-intensive jet fuel production volumes. ASTM D1655 also permits the co-processing of Fischer-Tropsch liquids, and the FT liquids produced by Fulcrum Bioenergy are currently used for potential co-processing in the Marathon Petroleum refinery.

It should be noted that the 5% bio-intermediate inserted will not translate into a 5% actual jet fraction as it will depend on the carbon chain-length of the bio-intermediate and the specific processing carried out in the refinery.

Direct thermochemical liquefaction pathways for SAF production (pyrolysis, catalytic pyrolysis and hydrothermal liquefaction)

Production of SAF via a bio-oil/biocrude intermediate has been challenging and is at a lower development stage than other pathways. Projects in the EU and US continue to explore the usage of sewage sludge and hydrothermal liquefaction as a pathway for SAF production, but this is still at a low TRL level. BTG-neXt is involved in research and technology development of advanced biofuels (including

SAF) from BTG pyrolysis bio-oils, while BTG Bioliquids technology was selected by Alder Fuels (Alder Renewables) as part of their SAF production pathway. Alder Renewables has a proprietary technology that produces Alder Renewable Crude (ARC) from pyrolysis bio-oil, which can be further upgraded into SAF. In collaboration with the National Renewable Energy Laboratory (NREL), a pilot skid for production of ARC was completed in May 2023 (TRL-6-7). However, it is not clear at this point what the TRL level for upgrading ARC into SAF is.

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1. Introduction

Aviation contributes to about 3% of the world's CO2e emissions, which amounts to about 915 million tonnes of CO2e per year. In 2021, the industry, as represented by the International Air Transport Association (IATA), committed to reaching net zero carbon emissions by 2050. A similar commitment was adopted by the International Civil Aviation Organisation (ICAO) in 2022. Progress in reaching these goals is being realized through multiple improvements in aircraft design, engine efficiencies, ground transport improvements, air traffic control systems and other measures. However, the use of SAF will play the most important role if the sector is to achieve its 2050 decarbonization targets (International Air Transport Association (IATA), 2022).

IATA's strategy toward net zero is summarised in Figure 1, where SAF use is expected to result in a reduction of about 65% of all emissions in the aviation sector (International Air Transport Association (IATA), 2022).

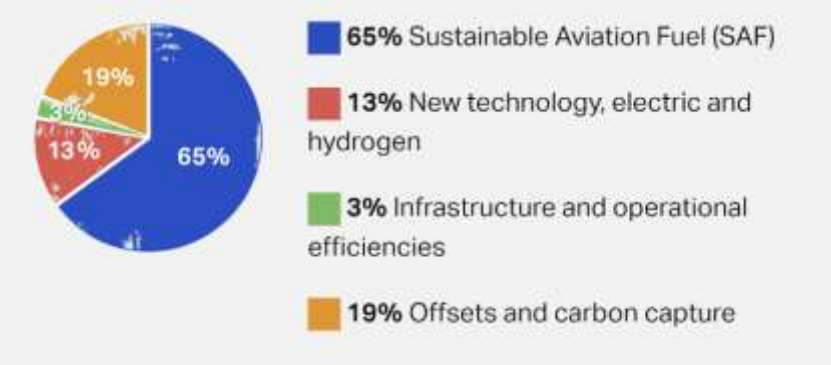


Figure 1 IATA's strategy to net zero by 2050 and the projected contribution of SAF

Although electrification and hydrogen are also expected to contribute to net zero aviation, the suitability of these technologies for different size aircraft and travel distances is limited (Figure 2), as the majority of emissions arise from long-haul passenger flights, where the only way to reduce emissions substantially is through the use of SAF.

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

Figure 2 An indicative overview of where low- and zero-carbon energy could be deployed in commercial aviation (ATAG, Waypoint 2050)

2. The climate impact of aviation – non-CO2 effects

Fossil-derived jet fuel combustion by aircraft emits CO2, NOx, SOx, water and particulate matter into the atmosphere. At high altitudes, this can form persistent contrail cirrus, resulting in a net warming effect. Some studies have suggested that the non-CO2 impacts can be significant, although quantifying these impacts has been challenging.

A fairly recent paper by Lee and colleagues presented a quantitative approach to evaluating the total climate impact of aviation (Lee et al., 2021). According to this study, contrail cirrus yields the largest positive net (warming) effective radiative forcing (ERF), followed by CO2 and NOx emissions.

2.1. Non-CO2 effects – persistent contrails

A report by the European Union Aviation Safety Agency (European Commission, 2020a) defines contrail cirrus as “an artificial cirrus-like cloud produced in the upper atmosphere (~ 8 to 12 km above ground) as a result of aircraft emissions of water vapour and soot particles into very cold atmospheres that are supersaturated with respect to ice”. Conditions of the atmosphere (temperature and ice supersaturation) dictate whether linear contrails form behind the aircraft and persist to produce larger-scale spreading of

the linear contrails into contrail cirrus. Contrails are considered long-lived if they persist for longer than 10 minutes (Kärcher, 2018). The net radiative force of contrails is dependent on “meteorological conditions, contrail characteristics, surface albedo, natural cirrus properties and coverage, as well as diurnal and seasonal cycles” (Teoh et al., 2020a). According to Teoh, the large uncertainty in quantifying the radiative forcing effect of contrail cirrus is due to uncertainties in “spatial distribution, contrail properties, and radiative transfer schemes” (Teoh et al., 2020b).

As the conditions around the aircraft (temperature and humidity) have an impact on the formation of persistent contrails, mitigating steps are being implemented that involve rerouting aircraft around areas with atmospheric conditions that will increase the risk of contrail cirrus formation. However, changing flight paths to avoid this effect may result in higher fuel consumption (Lee et al., 2021), which may result in a greater negative effect.

For purposes of this report, the impact of jet fuel chemistry on persistent contrail formation and the potential for SAF to mitigate these non-CO2 impacts are highlighted. Soot particles are formed during combustion and form nuclei to condense water vapour to form ice, leading to cloud formation and persistent contrails. Consequently, decreasing soot particle numbers reduces the number of ice particles formed and reduces contrail persistence. As the soot particle number is directly linked to the aromatic content of the jet fuel (European Commission, 2020b), therefore control of aromatics in the jet fuel can play a role in mitigating the climate impacts of aviation. Studies carried out by DLR and NASA have demonstrated this link with exhaust emissions and contrail characteristics measured during the flight of an Airbus 320 burning either standard jet fuels or low aromatic sustainable aviation fuel blends (Voigt et al., 2021a). This work demonstrated that soot particles can regulate the number of contrail cirrus ice particles forming during flights and that the use of low aromatic sustainable aviation fuel resulted in a 50-70% reduction in soot and ice number concentrations, resulting in less warming (Voigt et al., 2021b). The studies also suggested that bi-cyclic naphthalene aromatics were the biggest culprit in soot particle formation. The study concluded that lowering the jet fuel's aromatic content in general and bi-cyclic naphthalenes, in particular, can reduce the formation of persistent contrails. Consequently, this increases the net radiative forcing effects of aviation. Although these approaches can also be applied to conventional jet fuel to reduce non-CO2 impacts, using this strategy with SAF will allow a reduction in both CO2 emissions and non-CO2 impacts.

According to Teoh, only 2.2% of all flights contribute to 80% of the contrail effective radiative forcing in the region studied (Japan). These authors suggested that selectively diverting 1.7% of the airplanes could

reduce contrail cirrus impacts by up to 59.3% with only a 0.014% increase in total fuel consumption (Teoh et al., 2020a). In 2021, the Eurocontrol Maastricht Upper Area Control (MUAC) conducted contrail prevention trials with DLR, the German Aerospace Center, to better understand how air traffic management might reduce non-CO2 climate impacts. For example, MUAC investigated the role of operational measures such as changing flight levels (diverting aircraft up or down from their normal flight path) to reduce contrail cirrus formation. However, it was apparent that implementation of these measures needs accurate meteorological data to better identify areas with atmospheric conditions that create ideal conditions for persistent contrail formation.[2]

2.2 NOx emissions

The major source of NOx from fuel combustion in jet engines is thermal NOx emissions created through high-temperature reactions of nitrogen and oxygen present in the combustion chamber (Ommi & Azimi, 2012). The reaction is highly temperature-dependent, and therefore, thermal NOx formation can be reduced through combustion modification techniques, such as lean burn and RQL (Rich-burn, Quick-mix, Lean-Burn). These combustor designs have different strategies for NOx control, such as different approaches to fuel-air-mixture control through the combustor. (European Commission, 2020c). However, Skowron and colleagues point out that this may not always be the best solution as there is a trade-off between reduced NOx emissions and increased fuel consumption (Skowron et al., 2021).

2.3 The role of SAF/biojet in mitigating non-CO2 impacts

The NASA-DLR study has demonstrated that reductions in contrail cirrus formation and non-CO2 climate impacts could be obtained by using low aromatic fuels and from regulations to lower the maximum aromatic fuel content (Voigt et al., 2021b), even where conventional jet fuel is used. However, the use of SAF can reduce both CO2 and non-CO2 impacts at the same time. Many (but not all) types of SAF consist of predominantly paraffinic compounds such as alkanes, iso-alkanes, and cyclo-alkanes, with an aromatic content at zero or negligible. Of the current ASTM-approved pathways, FT-SPK/A, catalytic hydrothermolysis, and the recently approved pathway for mixed alcohols to jet (Swedish Biofuels) will all

[2] https://www.eurocontrol.int/article/reducing-impact-non-co2-climate-impact-eurocontrol-muac-and-dlr-partnering-contrail

contain aromatics. Future pathways such as SAF based on pyrolysis of hydrothermal liquefaction are also expected to contain aromatics.

When DLR-NASA tested SAF derived from the hydrotreated esters and fatty acids (HEFA) and SAF from Fischer-Tropsch synthesis, these types of SAF significantly lowered soot and ice particle formation. Soot emissions indices for the HEFA-based sustainable aviation fuel blends were 45–53% lower than the conventional Jet A1 fuel. The soot emission index for the FT-based SAF fuel also demonstrated reductions of ~50%, with soot particle reductions leading to 45–74% lower ice crystal apparent emission indices (EI) for the alternative jet fuel blends compared to conventional Jet A1 fuel.

The most significant soot emissions and ice crystal reductions are observed for SAF blends with a similar aromatic content to the other alternative fuel blends but containing a different sooting hydrocarbon family composition. This demonstrated that reducing hydrocarbons such as poly-cyclic aromatics in aviation fuels should reduce soot emissions (Voigt et al., 2021b).

However, having aromatics in jet fuel is essential for maintaining the swelling of nitrile O-rings used in aircraft to prevent fuel leakage (Narciso & Melo de Sousa, 2021). Therefore, jet fuel specifications, such as ASTM D1655, require a minimum aromatic content of 8%. Thus, for existing airplanes, this minimum aromatic content will be essential to ensure the safety of airplanes and passengers. Although newer O-rings manufactured from fluorocarbons do not require aromatics for swelling, it may take some time before all aircraft at a global level have been modified (Narciso & Melo de Sousa, 2021). While pure paraffinic SAF will achieve the greatest reductions in non-CO2 climate impacts, its use as an unblended fuel will be limited until safety considerations can be addressed.

As the aviation sector targets net zero by 2050, very high blends of SAF (up to 100% SAF) may be preferred. Therefore, ASTM is investigating the approval of a specification for 100% SAF. While there is some overlap in its application with respect to non-CO2 impacts, the use of 100% SAF targets CO2 impacts, while regulation of the types and percentage of aromatics will target non-CO2 impacts. It should be noted that ASTM specifications are not designed to address climate impacts but to ensure aircraft safety and operations.

In summary, to reduce the non-CO2 climate impacts based on the fuel chemistry, the allowed aromatic content and the aromatic hydrocarbon chemistry must be changed.

Although, from a refining perspective, the aromatic content in conventional jet fuel can be decreased through hydrotreatment/hydrocracking, this will result in higher overall production cost and energy

consumption (European Commission, n.d.). Within the SAF arena, reduced aromatics can be achieved by blending an aromatic SAF with a paraffinic SAF (thereby adjusting the aromatic content).

To reduce the non-CO2 climate impact of aviation, reducing the aromatics in aviation fuel can be done (Landera et al., 2022), and as cycloalkanes display some o-ring swelling behavior, they could be an attractive substitute for aromatics in jet fuel. Cyclo-alkanes have a higher energy density than iso-alkanes without negative properties such as low freezing point, high smoke point and thermal stability. By increasing the cyclo-alkane content in biojet/SAF, a higher density can be achieved than with a paraffinic SAF, reducing the amounts of aromatics while still meeting the minimum density specification of 775 kg/m^3 at 15°C (de Klerk et al., 2022). The ability of cyclo-alkanes to replace the swelling potential of aromatics makes them very promising alternatives to aromatics in biojet/SAF (Z. Yang et al., 2022).

Recent work has demonstrated that cyclo-alkanes are likely to induce swelling in silicon, extracted nitrile rubber, and poly(butadiene) o-rings but less likely to induce swelling in fluorocarbon, poly(acrylonitrile), epoxide, acrylonitrile butadiene styrene and fluorinated ethylene propylene o-rings (Landera et al., 2022). At low blends (10% wt), these researchers showed that unsubstituted cyclo-alkanes can achieve jet-A specifications but not at higher blends.

Although commercial processes do not yet exist for producing cycloalkanes from olefins, the oligomerization catalysis for producing iso-alkanes can be tuned for cyclo-alkanes through catalytic, selective cyclization of olefins. Research and development by Purdue University, PNNL and Lanzatech (Kilaz, 2023) to produce cyclo-alkanes from ethanol is ongoing.

3. Net zero by 2050 – targets and volumes of SAF required

Two recent reports for the aviation sector have estimated the amounts of SAF that will be required by 2050 to meet net-zero targets. They include the World Economic Forum-Clean Skies for Tomorrow report prepared by McKinsey, “Sustainable aviation fuels as a pathway to net zero”(McKinsey, 2022), and the ICF report prepared for ATAG’s Waypoint 2050, “Fueling net zero” (Blanshard et al., 2021). The ICF analysis estimated that between 330 and 445 million tonnes (412 – 556 billion litres) of SAF (alongside technological and operational improvements) will be required for the global aviation industry to achieve net-zero carbon emissions by 2050 (Blanshard et al., 2021). The WEF-CST report estimated that up to 520 million tonnes (650 billion litres) of SAF will be required by 2050 (McKinsey & Company, 2020).

More recently, the IATA Infrastructure Roadmap was published, which included an analysis indicating that more than 400 million tonnes of SAF will be required annually (International Air Transport

Association (IATA), 2023). Current production of SAF in 2023 is under 300 million liters per year. Although there should be a significant increase in the number of facilities that will be producing SAF in the short-to-medium term, these targets will be difficult to achieve.

It should be noted that many companies and countries have committed to 10% SAF consumption by 2030. The SAF Grand Challenge is targeting 3 billion gallons (11.355 billion litres) in the US by 2030. A 5% SAF blend in the EU will require 2.3 million tonnes of SAF (2.8 billion litres) (EASA 2022).

4. SAF-production facilities – existing, under construction and planned

According to a recent Argus Media webinar, 142 facilities have been announced, with a capacity of about 33 billion litres per year. However, it should be noted that most of these facilities are only in the early stages of planning. In many cases, the actual SAF volumes that might be produced are not clear, as SAF will only form a fraction of the capacity (based on information from Argus Media). As summarised in Figure 3, when considering the number of facilities based on technology and region, many announced facilities may not be included in this figure due to rapid and ongoing developments. In addition, some facilities have not specifically indicated that they will produce SAF, but they could potentially produce a SAF fraction. Consequently, this summary likely provides only a rough estimate of potential SAF plants and potential production volumes.

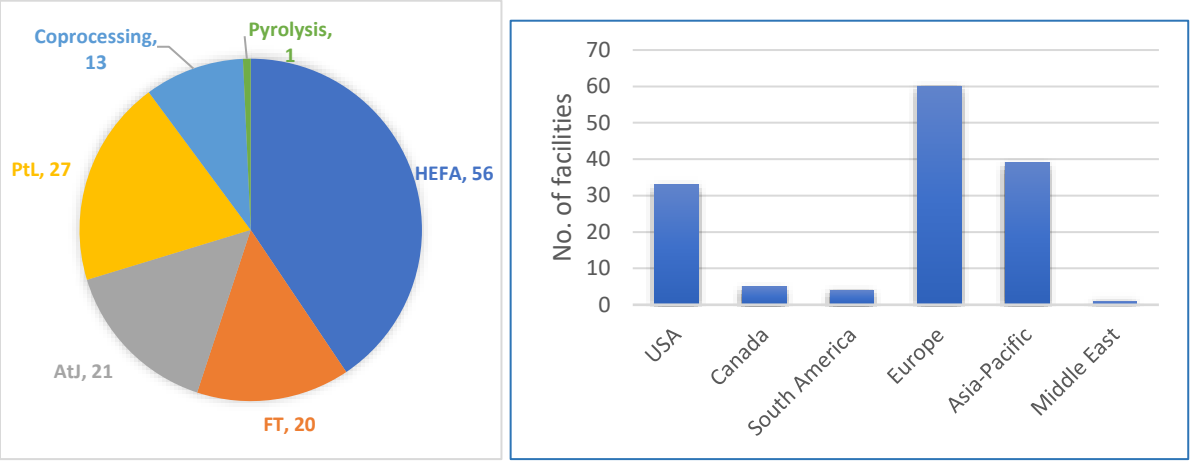


Figure 3 Current SAF facilities, planned and under construction based on technology and region (based on information from Argus Media)

It should be noted that, apart from the HEFA and lipid co-processing technology, the other technologies are still not yet at a commercial scale and may take longer to reach TRL 9. There is also uncertainty around the SAF fraction as part of the overall production volumes.

5. Technology pathways – opportunities, challenges and main research trends

Currently, ten SAF production pathways have been approved by ASTM, eight under ASTM D7566 and two co-processing pathways under D1655. Most recently, the Swedish Biofuels process was approved under ASTM D7566 (Annex 8).

The pathways under D7566 are summarised below:

- Annex A1: The Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene (FT SPK) pathway was approved in 2009 for blend levels up to 50%.
- Annex A2: The Synthesized Paraffinic Kerosene from Hydroprocessed Esters and Fatty Acids (HEFA SPK) pathway was approved in 2011 for blend levels up to 50%.
- Annex A3: The synthesized iso-paraffins (SIP) produced from hydroprocessed fermented sugars pathway was approved in 2014 at blend levels up to 10%.
- Annex A4. The Fischer-Tropsch Synthesized Kerosene with Aromatics (FT SPK/A) pathway was approved in 2015 for blend levels up to 50%.

- Annex A5. The Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) pathway was approved in 2016 (using an isobutanol intermediate) and 2018 (using an ethanol intermediate) for blend levels up to 50%.
- Annex A6: The Catalytic Hydrothermolysis jet (CHJ) pathway received approval in February 2020. Blends are currently limited to 50%.
- Annex A7: The HC-HEFA pathway involves the production of paraffins from bio-derived lipids hydrocarbons (tri-terpenes) from *Botryococcus braunii,* a microalgal species, and up to 10% blends with conventional petroleum jet fuel are permitted. This was the first SAF approved through the fast-track ASTM qualification process.
- Annex A8: The Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA) was approved in 2023. Required to be blended with petroleum-based jet fuel, up to a 50% maximum level. Any C2-C5 alcohols (individually or combined) can be used to produce jet fuel, but the aromatic and non-aromatic components must be produced in separate pathways.

Co-processing involves the insertion of biobased intermediates into existing petroleum refineries for simultaneous processing with petroleum feeds. Co-processing for the production of lower carbon intensity jet fuel falls under ASTM D1655 approval, which is the specification for conventional jet fuel. Co-processing of lipids was granted ASTM approval in April 2018 based on an amendment to the ASTM1655 standard. Co-processing of up to 5% lipids is permitted in petroleum refinery processes, provided that hydrotreatment is one of the processing steps. In addition, the co-processing of Fischer-Tropsch liquids at 5% blends in existing refineries was also approved in 2020. Increasing the co-processing limit to 30% is under review by an ASTM subcommittee. It should be noted that increasing this limit can lead to a dramatic increase in lower carbon intensity jet volumes as co-processing is becoming more prevalent with multiple refineries in Europe co-processing.

Other pathways in the D4054 process for testing and approval include methanol-to-jet, plastics-to-jet, and jet fuel production from pyrolysis of waste tires. Testing under ASTM D4054 for the methanol-to-jet pathway has proceeded based on volumes supplied by ExxonMobil, Haldor Topsoe and Honeywell-UOP. In addition, Virent has an application in progress under ASTM D4054 based on the production of a pure aromatic stream (synthetic aromatic kerosene, SAK) that can be blended with synthetic paraffinic kerosene (SPK) from pathways such as HEFA or FT. The recent transatlantic flight by Virgin Atlantic using 100% SAF used a blend of HEFA-SPK (88%) and Virent SAK (12%) to give a fully drop-in alternative jet

fuel. Virent is near completion of the final round of testing, and a ballot under a new D7566 Annex is imminent.

5.1 HEFA

5.1.1 Current status of HEFA technology and trends

The HEFA pathway is fully commercial and there has been a rapid expansion of new facilities based on this technology pathway. The main product of these facilities is renewable diesel, but some facilities also produce a SAF fraction. While the Neste and World Energy facilities have been producing SAF for several years, there are now a large number of facilities targeting SAF production. This is arguably a direct result of favourable SAF policies in the US and EU. However, as shown in Section 5.1.4, the competition between SAF and renewable diesel is significant, as it might be more economically attractive to produce renewable diesel rather than SAF.

5.1.2 The critical challenge of the lipid/HEFA pathway – feedstock availability and sustainability

The lipid/HEFA pathway is fully commercial and has no substantial technical challenges. The most critical challenge lies in feedstock availability and sustainability. Vegetable oils are produced globally at significant volumes, about 220 million metric tons per year. The largest volumes are produced from palm oil, soybean oil, and rapeseed oil (Figure 4). Even if all of these vegetable oils could be sustainably used for SAF production, it would be unable to meet the more than 400 billion litres of SAF required by 2050.

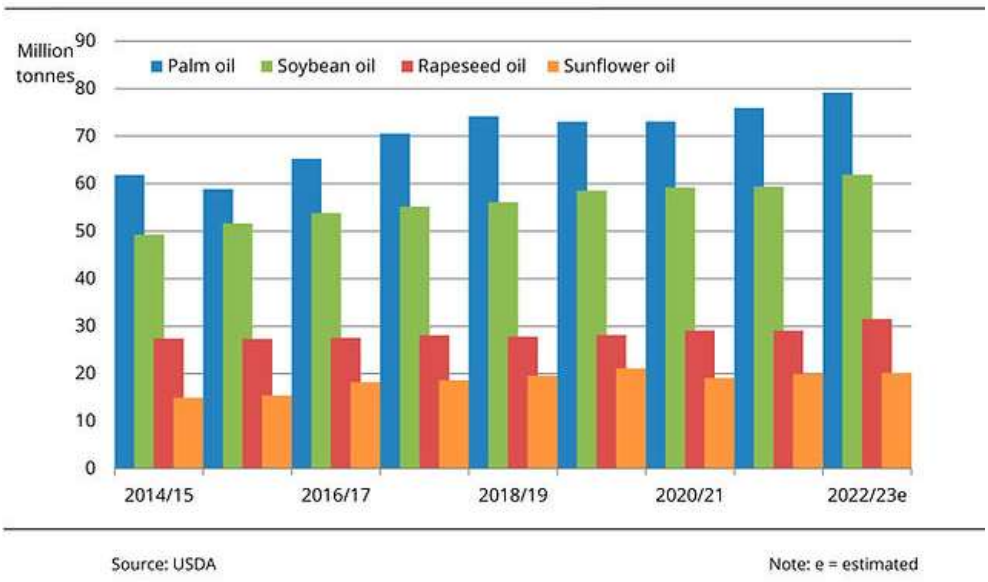


Figure 4 Global vegetable oil production for major crops (Source: US Department of Agriculture)

Although all three sources of vegetable oils have been used for biodiesel and renewable diesel production, these lipids are mainly used for food purposes. In the transport sector, particularly aviation, crop-based biofuels have a negative public perception. For example, several reports have assessed feedstock availability for SAF production but do not include any crop-based lipids (Blanshard et al., 2021; McKinsey & Company, 2020).

Therefore, the lack of affordable feedstock for HEFA-based SAF production is a critical challenge for this technology. For example, the International Energy Agency (IEA) recently warned that "demand is approaching the supply limits of the most-used wastes and residues"[3]. A recent SAF report prepared by McKinsey for the World Economic Forum-Clean Skies for Tomorrow (WEF-CST) estimated volumes of waste fats and oils of 11-13 million tonnes of used cooking oil, 12-15 million tonnes of rendered fats (tallow), and 11-14 million tonnes of other waste oils (a total of ~34-42 million metric tonnes). This estimate is in general agreement with projections from other sources, and based on the limited availability of waste fats and oils, it is estimated that HEFA could only supply about 10% of global SAF demand (Blanshard et al., 2021).

As demand for waste oils and fats increases, the potential for fraud is becoming a significant problem (Transport & Environment, 2023). In Europe, 80% of UCO supply is derived from imports, with 60% of all imports from China. Multiple investigations indicate that a large share of UCO imports are fraudulent and potentially repurposed palm oil (Transport & Environment, 2023).

Other sources of non-crop-based lipids include lipids from oil trees on degraded land, such as jatropha, and oil cover/intermediate crops (inedible oils), such as camelina, carinata (McKinsey & Company, 2020), as well as algal lipids. However, commercial cultivation has been very limited, and these feedstocks are not actually available for SAF production at this stage. While cover/intermediate crops grown in rotation can provide low carbon intensity feedstocks, commercial cultivation has been limited to date. Although several challenges have been identified, the availability of crop insurance is an important factor (Demsky, 2023). Several other challenges have been identified by Liu and colleagues, for example, farmers' concerns about potential negative impacts on their primary cash crop (such as a reduction in yield), additional input costs for the cover crops, and insufficient monetary incentives (Liu et al., 2023).

[3] https://www.iea.org/data-and-statistics/charts/biofuel-demand-share-of-global-wastes-and-residues-main-case-2010-2027; https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch

It is worth emphasizing that expanding the availability of sustainable lipids will be critical for SAF derived via the lipid/HEFA pathway. In the EU, many projects are being undertaken to cultivate biomass in contaminated and degraded lands for SAF production (e.g., Horizon2020 BIKE [4]). The JRC also published a report within the BIP (Biomethane Industrial Partnership), which reports the state-of-the-art of such projects, as well as opportunities and barriers at the EU level using marginal lands for biofuel production[5].

5.1.3 Companies and projects – operational and planned

A substantial number of new facilities for SAF production via the hydrotreatment of fats and oils have been recently announced. A list of some of these facilities based on Argus Media is shown in Table 1. The indicated capacity refers to the total volumes of total biofuels, not just SAF.

Table 1 List of operational and planned facilities for the production of HEFA-SPK based on oils and fats (not comprehensive) (Source Argus Media)

Company name	Location	Region	Capacity (t/yr)	Capacity (ML/Y)	Status
Montana Renewables	Great Falls, Montana	USA	173000	216.3	Planned
Covenant Energy	Southern Saskatchewan	Canada	134000	167.5	Planned
Indaba Renewable Fuels	Missouri	USA	276000	345.0	Planned
NEXT Renewables	Port Westward, Oregon	USA	550000	687.5	Planned
Green Energy Transformation Inc	Calgary	Canada	288000	360.0	Planned
Refuel Energy Inc.	Ontario	Canada	125000	156.3	Planned
Phillips 66	Rodeo, California	USA	220000	275.0	Planned
World Energy	Paramount, California	USA	576000	720.0	Planned
Braya Renewables	Newfoundland	Canada	187250	234.1	Planned
Indaba Renewable Fuels	California	USA	267000	333.8	Planned
World Energy	Paramount, California	USA	144000	180.0	Operating
Brasil Biofuels	Manaus, Brazil	Brazil	213000	266.3	Planned
Readifuels	Hull, Iowa	USA	36 MGPY	144	Planned
AIC Energy	Williams County, North Dakota	USA	288000	360.0	Planned
Bio D		South America	144000	180.0	Planned
World Energy	Houston, Texas	USA	720000	900.0	Planned
Diamond Green Diesel	Port Arthur, Texas	USA	677000	846.3	Planned
Fidelis New Energy	Baton Rouge, Louisiana	USA	1772000	2215.0	Planned
SGP Bioenergy	Colon & Balboa, Panama	South America	3745000	4681.3	Planned

[4] https://www.bike-biofuels.eu/the-project/ , BIO4A https://www.bio4a.eu/
[5] https://bip-europe.eu/2023/12/14/task-force-3-publishes-report-on-feedstock-potentials-from-marginal-and-contaminated-lands/

ECB Group	Vileta, Paraguay	South America	400000	500.0	Planned
Beijing Haixin Energy Technology	Anyang, Henan, China	Asia-Pacific	15000	18.8	planned
Sanju Biofuels	Anyang, Henan, China	Asia-Pacific	15000	18.8	planned
JGC/Revo/Kansai	Sakai, Osaka	Asia-Pacific	23	0.03	planned
EnNEOS/TotalEnergies	Wakayama, Japan	Asia-Pacific	300000	375.0	planned
Haike	Dongying, Shandong, China	Asia-Pacific	500000	625.0	planned
EcoCeres	Zhangjiagang, Jiangsu, China	Asia-Pacific	50000	62.5	planned
Jiaao	Guanyun, Jiangsu, China	Asia-Pacific	500000	625.0	planned
BioTech Energy	Sheikhupura, Pakistan	Asia-Pacific	20000	25.0	planned
Oriental Energy	Moaming, Guangdong, China	Asia-Pacific	1000000	1250.0	planned
BSGF	Bangkok, Thailand	Asia-Pacific	278000	347.5	planned
Chandra Asti/LX International	Cilegon, Banten, Indonesia	Asia-Pacific	300000	375.0	planned
Plaju	Pertamina, Indonesia	Asia-Pacific			planned
Cilacap	Pertamina, Indonesia	Asia-Pacific	334000	417.5	planned
ECO Environmental	Zhangjiagang, Jiangsu, China	Asia-Pacific	50000	62.5	operational
Sinopec	Zhenhai, Zhejiand, China	Asia-Pacific	80000	100.0	operational
Vandelay Ventures/Suria Capital	Kota Kinabalu, Sabah, Malaysia	Asia-Pacific	250000	312.5	planned
Petronas/ENI/Euglena	Penerang, Johor, Malaysia	Asia-Pacific	275000	343.8	planned
EcoCeres	Johor, Malaysia	Asia-Pacific	250000	312.5	planned
Sichuan Jinshang Environmental Technology	Suining, Sichuan, China	Asia-Pacific	200000	250.0	planned
LG Chem/Dansuk	Daesan, South Korea	Asia-Pacific	150000	187.5	planned
Dansuk	Gusan, South Korea	Asia-Pacific	300000	375.0	planned
Hyundai Oilbank	Daesan, South Korea	Asia-Pacific	100000	125.0	planned
Neste	Singapore	Asia-Pacific	1000000	1250.0	planned
BP	Kwinana, Western Australia	Asia-Pacific	330000	412.5	planned
Oceania Biofuels	Queensland, Eastern Australia	Asia-Pacific	266000	332.5	planned
Ampol/ENEOS	Brisbane, Queensland, Australia	Asia-Pacific	190000	237.5	planned
ST1 &	Gothenburg, Sweden	Europe	70000	87.5	planned
ST1 & SCA	Ostrand, Sweden	Europe			planned
TotalEnergies	Grandpuits, France	Europe	210000	262.5	planned
Repsol	Cartagena, Spain	Europe	50000	62.5	planned
Cepsa/Apical	Andalusia, Spain	Europe			planned
ENI	Gela, Italy	Europe	150000	187.5	planned
Shell	Rotterdam	Europe	436000	545.0	planned
SkyNRG	Delfzijl	Europe	100000	125.0	planned
Neste	Rotterdam	Europe	500000	625.0	planned
Firefly Green Fuels	SouthEast UK	Europe	100000	125.0	planned

5.1.4 Increasing the SAF fraction in lipid/HEFA facilities

Hydrotreatment of fats, oils, and greases has been used to make renewable diesel for many years, but until recently, only World Energy and Neste have produced SAF routinely.[6] The main reason for this was economics as, typically, it was not cost-effective for HEFA facilities to produce SAF as it was cheaper to produce renewable diesel alone. At the same time, incentives have generally favoured the production of renewable diesel rather than SAF. Although the US's Inflation Reduction Act introduced a higher incentive for SAF than for renewable diesel, SAF production competes with road transportation fuels (bio/renewable diesel). Hydrocarbons with chain lengths in the gasoline, jet and diesel range are produced in refineries based on the selected cut-off points during distillation. Consequently, competition between SAF and low CI gasoline/diesel fuels will occur in most technology pathways.

As shown in Figure 5, the boiling point ranges of the gasoline, jet, and diesel fractions overlap. The boiling point is used for fractionation in a refinery, and typically, the refiner chooses boiling point cutoffs to produce products based on market conditions. Depending on the economics and the availability of favourable incentives for various products, fractionation can be carried out to shift a larger fraction to the diesel or gasoline pool. This provides greater flexibility in terms of the carbon chain lengths. While this will apply to all technology pathways that produce a range of molecules, it is specifically applicable to the HEFA pathway as the oils and fats used have carbon chain lengths that typically fall within the diesel range (average C18 fatty acid chain length). After upgrading, a smaller fraction of feedstock molecules will fall in the jet range due to some cracking taking place during hydrotreatment (~15%). This can be separated from the diesel fraction through fractionation. However, this usually requires additional infrastructure at an additional cost, such as a distillation column.

[6] Neste produced SAF batchwise with distillation and fractionation taking place at a different location to the refinery.

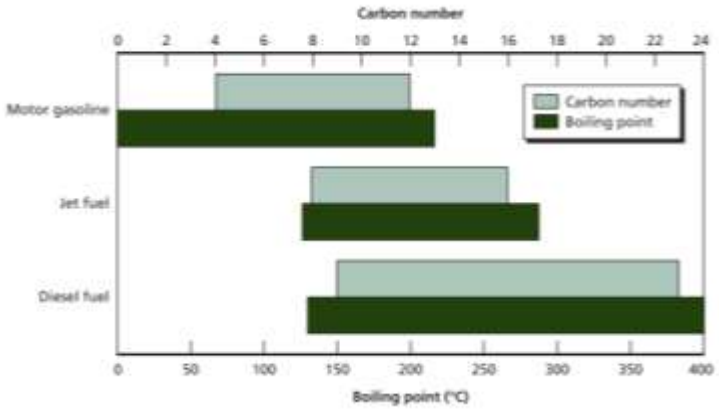


Figure 5 Carbon number and boiling point range for gasoline, jet fuel and diesel.

As was discussed in the 2021 report on biojet/SAF, it is possible to produce a larger SAF fraction with additional hydrocracking carried out to reduce the size of the diesel range molecules and obtain a greater jet fraction. However, as the cracking is not very specific, this increases the production of small molecules in the gas range, thereby reducing the yield of liquid fuel products. In addition, the gases that are formed have low value, reducing overall revenue.

However, as new SAF policies in the EU and USA have been introduced, there is more pressure on HEFA biorefineries to produce SAF. Many refineries have indicated their intention to shift up to 70% and some up to 100%. In order to produce high SAF fractions economically, recent research has focused on developing new catalysts that can maximise SAF production but with minimum loss to overall yield. Several catalyst companies are now offering new isomerization catalysts that can maximize the SAF fraction in a HEFA facility[7] without yield loss.

In recent work, Misra and colleagues published an excellent review on catalyst development for isomerization to increase the SAF fraction but involving less cracking (Misra et al., 2023). Although isomerization in a HEFA facility is essential to create branched iso-paraffins with improved cold-flow properties, hydro-isomerization can sometimes lead to excessive cracking and loss of product yield, particularly in the case of paraffin-rich hydrocarbons such as oils and fats feedstocks (Misra et al., 2023). While noble metals, such as Pt and Pd, are very effective for hydroisomerization, they are expensive and more susceptible to contaminants and deactivation. Other types of catalysts include zeolite-based hydroisomerization catalysts, SAPO molecular sieves, sulfated and tungstated zirconia catalysts,

[7] In personal communications with several companies, it is claimed that no cracking takes place.

mesoporous metal oxide-based catalysts, chlorinated alumina catalysts and heteropolyacid catalysts. Each of these catalysts has advantages and disadvantages, which are discussed at length (Misra et al., 2023). In other published work, Glowka and colleagues investigated Pt/(SAPO-11 + Al2O3) catalyst, Yang and colleagues evaluated Pt/SAPO-11 molecular sieve catalyst, while Schmidt researched MTT- and TON-type zeolites and Schmutzler bifunctional Pt/H-ZSM-5 catalysts (Główka et al., 2024; Schmidt et al., 2023; Schmutzler et al., 2021; S. Yang et al., 2023). Further reviews by Aljajan and Mäki-Arvela also explore this topic (Aljajan et al., 2023; Mäki-Arvela et al., 2018).

5.1.5Pretreatment of feedstocks and trends

Typically, biobased feedstocks contain contaminants, such as alkali metals (Mg, Na, K), phospholipids, chloride, etc., that will deactivate and inhibit catalysts in downstream catalytic processes. These contaminants are generally removed in a pretreatment step that could involve processes such as acid washing (degumming to remove phosphorus from phospholipids), bleaching (filtration using active clay), centrifugation, filtration and enzymatic treatment.

Companies such as Axens, Alfa Laval, Sulzer, W.R. Grace and Desmet Ballestra have all developed pretreatment technologies for fats, oils and greases that can be used by a HEFA refinery to remove contaminants, while companies such as Neste and REG have their own pretreatment technologies.

As biorefineries are shifting towards using more low carbon-intensity feedstocks such as used cooking oil (UCO), tallow, etc., the quality of the feedstocks is typically lower, with different types of contaminants needing to be addressed during pretreatment steps. For example, UCO and animal fats contain polyethylene (from plastics), which is typically not found in vegetable oils.

The company Desmet Ballestra provides some interesting information about the types and concentrations of contaminants found in different lipid feedstocks

Table 2 [8].

[8] https://www.biobased-diesel.com/post/requirements-and-solutions-for-pretreatment-of-hvo-feedstocks

Table 2 Quality parameters of different lipid feedstocks for HEFA production (Source – Desmet Ballestra https://www.biobased-diesel.com/post/requirements-and-solutions-for-pretreatment-of-hvo-feedstocks) FFA=free fatty acids

Raw Material	FFA	P	Metals	N	S	Cl (total)	Polyethylene
	%	ppm	ppm	ppm	ppm	ppm	ppm
Edible Vegetable Oils	< 3	50-250	100-300	30-200	2-20	< 5	-
Crude Palm Oils	< 6	15-30	20-60	10-20	< 10	< 15	-
Used Cooking Oils	1-10	< 20	< 50	5-15	10-100	20-100	0-200
Animal Fats	2-35	50-1000	200-2000	50-1500	20-200	50-500	0-1000
Acid Oils	50-60	50-1000	100-1000	50-250	20-100	<25	-
Palm Fatty Acid Distillates	> 85	< 5	< 10	< 10	< 10	< 10	-

Every biorefinery will set its own specifications for acceptable levels of contaminants. Consequently, the specifications for different companies (Table 3) will depend on the specific refinery configuration and other factors that would allow the handling of different contaminants. Nitrogen and sulfur are routinely removed through hydroprocessing, although the concentration will impact the hydrogen demand of the refinery.

Table 3 Inlet product specifications for different HEFA refineries (Source – Desmet Ballestra https://www.biobased-diesel.com/post/requirements-and-solutions-for-pretreatment-of-hvo-feedstocks)

Component	Unit (max)	Official Methods	Provider A	Provider B	Provider C	Provider D
Free Fatty Acids	%	AOCS Ca 5a-40	5	20	20	95
Moisture Content	ppm	ISO 8534:2017 AOCS Ca 2e-84	500	500	700	500
Insoluble Impurities	ppm	AOCS Ca 3a-46	500	500	100	500
Unsaponifiable	%	AOCS Ca 6a-40	NS	1	1	NS
Phosphorus	ppm	AOCS Ca 17-01	3	3	2	3
Metals (Total*)	ppm	AOCS Ca 17-01 ASTM D5185	10	5	5	10
Nitrogen	ppm	ASTM D4629	50	350	100	350
Sulfur	ppm	ASTM D2622 ASTM D4294 ASTM D5453	100	250	30	100
Chlorine (total)	ppm	EN 14077 ASTM D7359	10	50	5	50
Polyethylene	ppm	AOCS Ca 16-75	50	50	50	50

NS: Not Specified
*Ca, Mg, Fe, Na, K, B, Si, Zn, Al

A recent interview with alfa laval provided substantial insight into contaminants and pretreatment approaches for different feedstocks [9]. Waste feedstocks such as UCO and palm fatty acid distillates typically contain high concentrations of free fatty acids. The high acidity of these feedstocks could cause corrosion and other problems, which might require corrosion-resistant metallurgy or blending with other feedstocks to reduce acidity. Plastic residue can be found in tallow from meat packaging, while UCO may contain particulate contaminants from the cooking process as well as plastic residue. It should also be noted that during the pretreatment process, wastewater is generated and must be treated, and spent bleaching earth must be landfilled or otherwise disposed of.

Although pretreatment can be carried out by the feedstock supplier or at the biorefinery, biorefineries have generally not carried out their own pretreatment. However, as there is an ongoing shift to lower-quality feedstocks, more biorefineries are investing in their own pretreatment units. This can provide greater flexibility in feedstock sourcing and ensure high-quality standards are maintained. However, it should be noted that pretreatment carried out at the biorefinery will require an investment in additional infrastructure.

Recent work describes a different type of pretreatment developed by Applied Research Associates (ARA) as part of their catalytic hydrothermolysis process. The Hydrothermal Cleanup (HCU)[10] process uses water at high temperatures and pressure to remove metals and other inorganics[11]. Organically bound metals and inorganic contaminants are removed while acidulating soaps and hydrolyzing phospholipids into diglycerides and phosphate salts. An HCU pretreatment unit was recently installed at Montana Renewables [12].

An alternative pretreatment process for very poor-quality feedstocks involves fat splitting followed by fatty-acid distillation. Fat splitting uses water at high pressures and temperatures but can also be carried out by enzymes.[13]

[9] https://www.alfalaval.com/industries/food-dairy-beverage/webinars/introduction-to-hvo-rd-pretreatment/faq-hvo-pretreatment-standard/

[10] https://www.ara.com/products/renewable-diesel-pretreatment-fat-oil-grease-cleanup/

[11] Similar to hydrothermal liquefaction

[12] https://www.ara.com/news/aras-hydrothermal-cleanup-hcu-pretreat-has-launched-at-montana-renewables/

[13] https://www.desmet.com/oleochemicals-hvo-biodiesel/oleochemicals/fatty-acids; https://www.crowniron.com/oleochemicals/fat-splitting/

5.1.6 The Carbon intensity (CI) of SAF derived via the HEFA pathways

When the default carbon intensity values from ICAO CORSIA are summarised (Table 4), waste feedstocks such as UCO and tallow do not incur any induced land use change (ILUC) and achieve very low carbon intensities. Alternatively, crop-based feedstocks have high ILUC values, which reduces the potential emissions reductions that can be achieved. Although dedicated crops such as jatropha and cover crops such as carinata and camelina can achieve very low carbon intensities, they are not readily available.

Table 4 CORSIA default life cycle emissions values for CORSIA Eligible Fuels produced with the HEFA fuel conversion process

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Global	Tallow		22.5	0.0	22.5
Global	Used cooking oil		13.9		13.9
Global	Palm fatty acid distillate		20.7		20.7
Global	Corn oil	Oil from dry mill ethanol plant	17.2		17.2
USA	Soybean oil		40.4	24.5	64.9
Brazil	Soybean oil		40.4	27.0	67.4
Global	Soybean oil		40.4	25.8	66.2
EU	Rapeseed oil		47.4	24.1	71.5
Global	Rapeseed oil		47.4	26.0	73.4
Malaysia & Indonesia	Palm oil	At the oil extraction step, at least 85% of the biogas released from the Palm Oil Mill Effluent (POME) treated in anaerobic ponds is captured and oxidized.	37.4	39.1	76.5
Malaysia & Indonesia	Palm oil	At the oil extraction step, less than 85% of the biogas released from the Palm Oil Mill Effluent (POME) treated in anaerobic ponds is captured and oxidized.	60.0	39.1	99.1
Brazil	Brassica carinata oil	Feedstock is grown as a secondary crop that avoids other crops displacement	34.4	-20.4	14.0
USA	Brassica carinata oil	Feedstock is grown as a secondary crop that avoids other crops displacement	34.4	-21.4	13.0
Global	Brassica carinata oil	Feedstock is grown as a secondary crop that avoids other crops displacement	34.4	-12.7	21.7
Global	Camelina oil	Feedstock is grown as a secondary crop that avoids other crops displacement	42.0	-13.4	28.6
India	Jatropha oil	Meal used as fertilizer or electricity input	46.9	-24.8	22.1
India	Jatropha oil	Meal used as animal feed after detoxification	46.8	-48.1	-1.3

5.2 Catalytic hydrothermolysis

Catalytic hydrothermolysis (CH) uses the same types of feedstocks as the HEFA process but is a completely different technology. The biojet fuel produced through this process is fully drop-in, containing paraffins and aromatics (Eswaran et al., 2021). The process uses high pressures and

temperatures in the presence of water, similar to hydrothermal liquefaction. Catalytic hydrothermolysis (CH) is an integrated process that includes preconditioning, catalytic hydrothermolysis conversion, and post-fining (Eswaran et al., 2021). In addition, anaerobic fermentation can be used to produce hydrogen, volatile acids and alcohols from fermentable feedstocks. A preconditioning step includes conjugation, cyclization and cross-linking reactions to alter the fatty acid backbones of triglycerides. Preconditioning is claimed to reduce hydrogen consumption during post-refining by approximately 25 % compared to the direct hydrotreating approach. In the second stage, the feedstock is fed into the supercritical hydrothermal reactor, where reactions such as cracking, hydrolysis, decarboxylation, dehydration, isomerization, recombination and/or aromatization occur. In the final stage, hydrotreatment and fractionation take place.

The jet fuel produced in the CH process has a range of straight, branched, cyclic, and aromatic molecules, with a small fraction of gaseous products. According to Eswaran, the CH process has an approximate 30% selectivity toward the jet fuel range, compared with about 12.8% for the jet fuel range and 68.1% for the diesel range when the HEFA process is used. The CH process also consumes less hydrogen during upgrading (Eswaran et al., 2021). Catalytic hydrothermolysis jet (CHJ) is approved under ASTM D7566 Annex 6 at 50% blends (with conventional jet fuel). However, as it contains the whole range of molecules that are typically found in conventional jet fuel, it could potentially be used without blending.

5.3 Gasification and Fischer-Tropsch synthesis

Gasification is usually conducted under conditions of high temperature and pressure using air, oxygen or steam as a gasifying agent to convert biomass to a low to medium-energy gas known as synthesis gas or “syngas”. In the second stage, the synthesis gas is converted into liquid drop-in biofuels through two types of processes, namely Fischer-Tropsch synthesis or methanol to gasoline. However, prior to synthesis, the syngas needs to be cleaned so that it consists mainly of H2 and CO, the starting material for Fischer-Tropsch synthesis.

The process steps involved in the gasification/FT pathway are summarised in Figure 6. While gasification and Fischer-Tropsch as individual processes have been commercial for some time, the integrated process based on biobased feedstocks is not yet at a commercial scale.

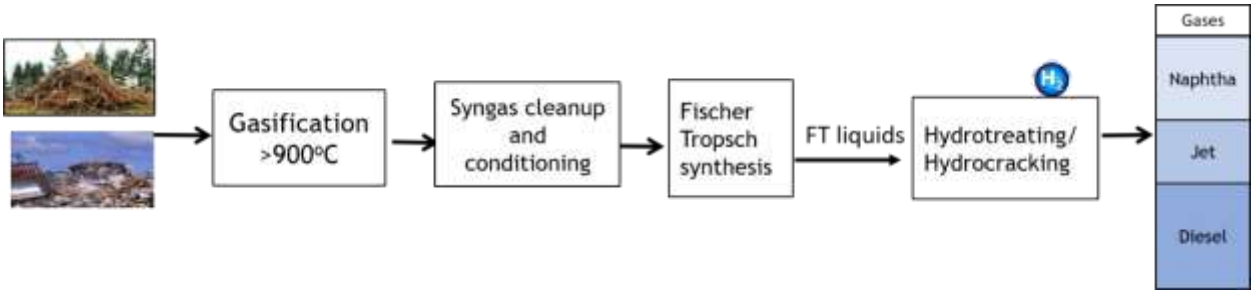


Figure 6 Diagram showing the steps in the gasification/FT pathway

The characteristics and chemistry of biobased feedstocks required syngas cleanup steps that will remove the tars and other specific contaminants that can deactivate the downstream catalysts in the FT process. Not only is syngas cleanup technically challenging, but it also contributes to the high production cost of fuel products. Furthermore, the high oxygen content in biobased feedstocks results in a low H2/CO ratio (0.8-1.1), which has to be adjusted to a ratio of about 2 before FT synthesis. While the H2/CO ratio can be adjusted through the water gas shift reaction, in the case of Fe catalysts, this results in a loss of carbon and a lower yield. Although four transitional metals can be used for FT synthesis, namely cobalt, iron, ruthenium and nickel (Shafer et al., 2019), only Co and Fe are generally used for industrial purposes and are the only two catalysts that can be used, currently, for ASTM D7566 approved SAF under Annex 1.

5.3.1 Current status of technology and trends

While a significant number of companies are at various stages of planning and construction, the Fulcrum Bioenergy facility in Nevada is currently the only one operating that is based on gasification and Fischer-Tropsch (FT) with Fulcrum using municipal solid waste (MSW) as its feedstock. In 2023, the gasification/FT approach suffered a setback in moving towards commercialization with the closure of Red Rock Biofuels before construction was completed. This facility planned to use forest residues as its feedstock.

The successful use of biomass feedstocks, such as forest residues, for gasification will be critical as SAF production will need to access a supply of cheap, abundant feedstocks. The company Enerkem, based in Edmonton, Canada, has been operating a gasification facility (based on MSW as a feedstock) for a number of years. However, Enerkem targets methanol as a product and does not use FT at this stage to produce hydrocarbons directly. Enerkem is also constructing a facility in Quebec, Canada, based on the gasification of forest biomass, where the main product will be methanol. The methanol can be converted into SAF through a methanol-to-jet conversion, and this technology will be discussed later.

5.3.2 Companies – operating, under construction and planned

According to Argus Media, a substantial number of SAF-producing companies are planned, but the list below is not comprehensive as new announcements are made on an almost weekly basis (Table 5).

Table 5 Companies that are planned or in operation and will use Fischer-Tropsch for SAF production (Argus Media with corrections and additions)

Company name	Location	Technology	Capacity (t/yr)	Capacity (ML/Y)	Status
Fulcrum Bioenergy	Gary, Indiana	FT	95000	118.8	Planned
Fulcrum Bioenergy	Reno, Nevada	FT	33000	41.3	Operating
DG Fuels	Louisiana	FT	503000	628.8	Planned
Castlerock Green Energy	Shelton, Washington	FT	58000	72.5	Planned
Velocys Bayou Fuels	Natchez, Mississippi	FT	72000	90.0	Planned
USA Bioenergy	Bon Weir, Texas	FT			Planned
Velocys/Toyo	Japan	FT			planned
WasteFuel	Manila, Phillipines	FT	86309	107.9	planned
Fulcrum & Essar Oil	Stanlow, UK	FT	83700	104.6	planned
Velocys	Immingham, UK	FT	50000	62.5	planned
Greenergy	Thames Enterprise Park, UK	FT			planned
Lighthouse Green Fuel	Billingham, Teeside	FT	86600	108.3	planned
Quantafuel	Eastern Norway	FT	6840	8.6	planned
TotalEnergies	BioTFuel, France	FT			planned
Repsol	Bilbao, Spain	FT	2100	2.6	planned
Enerkem	Rotterdam	FT	60000	75.0	planned
KLM	Vaxjo, Sweden	FT	16000	20.0	planned
Etihad/Tadweer	Abu Dhabi, UAE	FT	403000	503.8	planned

Two of the projects using gasification/FT should be mentioned: the Velocys, Bayou Fuels facility in Natchez, Mississippi and the DG Fuels facility in Maine. Both these facilities have incorporated extensive infrastructure and measures to reduce the carbon intensity of their fuel product significantly. For example, the Velocys, Bayou facility will be using additional measures such as 100% renewable power (from biomass) as well as carbon capture and storage [14]. The company claims that this will achieve fuels with a negative carbon intensity of -375g CO2e/MJ. The Bayou Fuels facility will have a capacity of 36 million gallons of fuel.

The DG Fuels plant in Louisiana, based on gasification/FT [15] , will have an announced capacity of 180 million gallons (~680 million litres). The large scale of this facility is notable compared with the Fulcrum

[14] https://velocys.com/projects/bayou-fuels/
[15] https://biomassmagazine.com/articles/dg-fuels-awards-contract-to-nextchem-for-us-saf-facility

Bioenergy facility at 10 million gallons. While FT has been demonstrated at these large scales by companies such as Sasol, such facilities used coal or natural gas as the feedstock. Achieving such a large scale based on biomass as a feedstock will likely present a challenge for this project.

In order to reduce the carbon intensity of their fuel product, DG Fuels will produce hydrogen through water electrolysis powered by wind- and solar-generated electricity (Figure 7). The feedstock used for gasification will be bagasse, sugar cane trash and pulp. The expected investment required to complete the facility is in excess of $4 billion [16], with additional infrastructure such as renewable power, desalination, and water electrolysis likely contributing to the high investment required. The plant is expected to be operational by 2028.

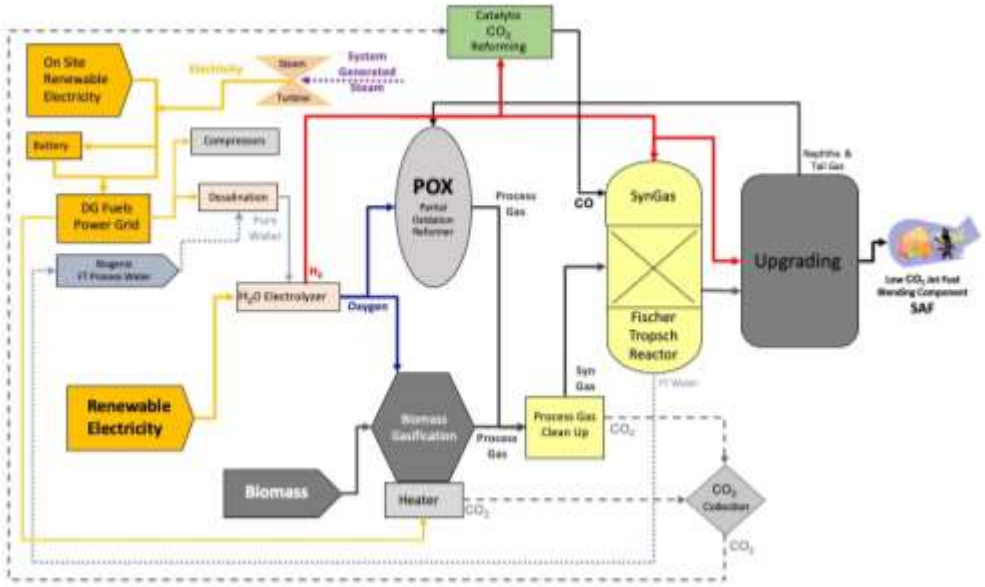


Figure 7 Illustration of the DG Fuels process for gasification and FT [17]

5.3.3 Improving the selectivity of Fischer-Tropsch for jet fuel

Syngas (CO + H2) produced during gasification is used in FT synthesis. Carbon monoxide and hydrogen adsorb on the catalyst surface, and chain growth takes place through carbon-carbon coupling. Chain growth continues by adding further CO and H_2 until the newly formed hydrocarbon molecule is desorbed from the catalyst surface. The C–C coupling during propagation is uncontrollable, and product

[16] https://www.greencarcongress.com/2023/07/20230729-dgf.html; https://dgfuels.com/2023/03/21/dg-fuels-proposes-4-2-billion-sustainable-aviation-fuel-complex-in-st-james-parish/
[17] https://dgfuels.com/technology/

distribution is described by the Anderson-Schulz-Flory (ASF) statistical model (Cheng et al., 2017). Figure 8 illustrates the typical product distribution under the ASF model, which is dependent on the chain growth probability factor (α). The chain growth factor is determined by the structure and composition of the catalyst and reaction parameters such as the temperature, partial pressure of syngas and H_2/CO ratio in the feed gas (Liu et al., 2011).

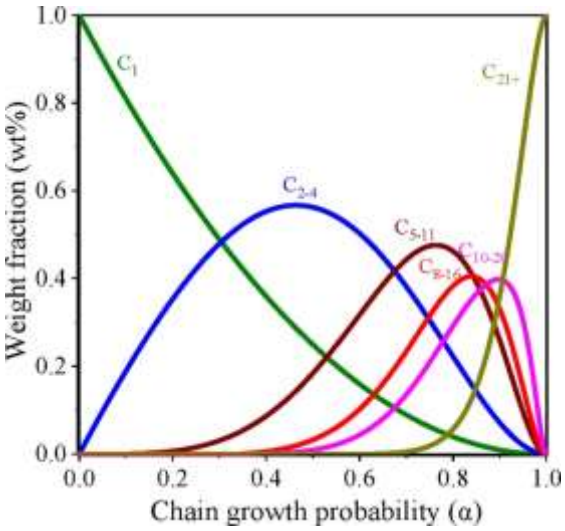


Figure 8 Illustration of product distribution under the ASF model, depending on the chain growth probability (α)(Lin et al., 2022)

According to Cheng, middle distillates cannot be obtained with high selectivity and the maximum selectivity of diesel-range (C_{10}–C_{20}) hydrocarbons is approximately 39% (α = 0.89) (Cheng et al., 2017; de Klerk, 2013). Although obtaining a narrow product distribution would be more energy and cost-efficient (Cheng et al., 2017), other work indicated that this would require the development of new catalysts and strategies that don't follow the ASF distribution (Cheng et al., 2017).

While obtaining a high chain growth factor can increase the selectivity of heavy products such as middle distillates, the ASF distribution gives a gradual increase in selectivity, which limits the formation of a specific fraction such as kerosene. Liu argues that it would, therefore, be preferable to produce hydrocarbons in an "anti-ASF" manner to obtain suitable middle distillates (Liu et al., 2011).

Based on FT synthesis that follows an ASF distribution, the maximum straight-run fraction of kerosene is about 40%. Although this fraction can be increased by methods such as the cracking of heavier hydrocarbons, it requires additional processing steps with greater CAPEX and OPEX. Obtaining a higher kerosene fraction on a straight-run basis is, therefore, highly desirable from a cost and energy perspective.

Obtaining a higher fraction of jet fuel via Fischer-Tropsch synthesis has become an important target of research and development. As well as impacting gasification-based pathways, it can also contribute to the power-to-liquids and alcohol-to-jet pathways, where some oligomerization configurations also follow the ASF distribution for products.

Companies such as Sasol and Topsoe have targeted improved FT catalysts and reactor designs to achieve higher selectivity to kerosene and diesel, while companies such as Topsoe are trying to improve hydrocracking and isomerization catalysts (e.g., TK-928 or TK-930) to provide high yields of jet and/or diesel (Malan, 2023).

Other areas of research have focused on the development of bifunctional catalysts containing zeolites with active sites for chain growth (FT active metals such as Fe, Co, Ni, and Ru) and acid sites for hydrocracking/isomerization, carried out simultaneously (Teimouri et al., 2021). Liu and colleagues have added water vapor to the FT process, which increased the formation of heavy products (C10+) by up to 87.3% in a manner that deviated from the ASF distribution model (Liu et al., 2011). In other work, Cheng and colleagues investigated the ability of bimetallic catalysts to increase selectivity. Using a Co/Na-meso-Y catalyst, a C10-C20 selectivity of 60% was achieved, significantly higher than the expected 39% based on the ASF distribution (Cheng et al., 2017).

5.3.4 Feedstocks for gasification/FT, availability and carbon intensity of SAF pathways

Multiple feedstocks can be used to produce SAF via gasification, including municipal solid waste, forest and agricultural residues, and dedicated energy crops such as miscanthus or poplar. Forest and agricultural residues are available in large quantities and are globally distributed. The McKinsey report estimated that about 580 million metric tonnes of forestry residues, 660 million tonnes of agricultural residues, 960 million tonnes of MSW and 320 million tonnes of wood-processing waste are available annually (McKinsey & Company, 2020), but this report did not take competition for feedstocks into account. Thus, it is considered to be an overestimate of available feedstock sources (Blanshard et al., 2021).

Overall, feedstock availability for SAF production via gasification is not seen as a major challenge. Rather, the challenge will be establishing mature supply chains for harvesting, collecting, and comminuting feedstocks and cost-effective aggregation of large-scale feedstock volumes to support large-scale commercial SAF production facilities. Due to its high water and oxygen content, the transport of forest residues is only economical over relatively short distances, while economies of scale require large

feedstock volumes. The development of advanced supply chains with intermediate densification via processes such as pelletization, torrefaction, and bio-oil production could offer potential opportunities. However, these are not yet at an advanced technology readiness level for the production of biofuels. Although the production of wood pellets is fully commercial for large-scale bioenergy applications, it provides a more expensive biomass feedstock. While agricultural residues are considered suitable feedstocks for gasification with FT, these residues have a high ash content, which introduces some technical challenges while producing high waste volumes and lower yields.

From a sustainability perspective, all gasification/FT pathways can deliver very low carbon intensity SAF, as demonstrated by the default CI values summarised in Table 6. It should be noted that, in the case of MSW, the non-biological content of the feedstock has the biggest impact on CI.

Table 6 Default carbon intensity values based on a life cycle assessment for SAF production from gasification and Fischer-Tropsch synthesis

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Global	Agricultural residues	Residue removal does not necessitate additional nutrient replacement on the primary crop	7.7	0.0	7.7
Global	Forestry residues		8.3		8.3
Global	Municipal solid waste (MSW), 0% non-biogenic carbon (NBC)		5.2		5.2
Global	Municipal solid waste (MSW) (NBC given as a percentage of the non-biogenic carbon content)		NBC*170.5 + 5.2		NBC*170.5 + 5.2
USA	Poplar (short-rotation woody crops)		12.2	-5.2	7.0
Global	Poplar (short-rotation woody crops)		12.2	8.6	20.8
USA	Miscanthus (herbaceous energy crops)		10.4	-32.9	-22.5
EU	Miscanthus (herbaceous energy crops)		10.4	-22.0	-11.6
Global	Miscanthus (herbaceous energy crops)		10.4	-12.6	-2.2

5.4 The Alcohol-to-Jet (AtJ) pathway

The alcohol-to-jet pathway can use a variety of alcohols for conversion in biojet fuel, with ethanol and isobutanol approved under ASTM D7566 Annex 5 and mixed alcohols (C2-C5) (based on the Swedish Biofuels process) under Annex 8. The conversion of methanol-to-jet is currently under consideration for approval by ASTM.

The basic steps for converting alcohol into jet fuel are dehydration, oligomerization, hydrogenation, and fractionation (Figure 9).



Figure 9 Basic steps in the alcohol-to-jet conversion process

These steps are at a commercial level as individual processes and have been used for decades to produce chemical intermediates. Ethanol conversion into renewable ethylene through dehydration has been commercially carried out by Braskem in Brazil for several years.

The conventional process for AtJ follows an initial step where ethanol is converted into ethylene (dehydration). Traditionally, the major dehydration catalysis involves the use of alumina and transition metal oxides, but more recently, silicoaluminophosphates, HZSM-5 zeolite and heteropolyacid catalysts have been used (Tao et al., 2017). Conversion of ethanol to close to 100% can already be achieved. Similarly, oligomerization of ethylene is a commercial process for the production of plastics, chemicals, detergents, etc. Direct conversion of ethylene into long hydrocarbon chains in the jet-range is possible but not very effective. Consequently, intermediate olefins (a mixture of C4-C10) are generally produced from ethylene as they are easier to oligomerize into jet fuel (Brooks et al., 2016).

The oligomerization step converts intermediate olefins such as butene into longer hydrocarbon chains, including jet-range products. Many of the catalysts used in oligomerization are based on Ziegler–Natta type systems, which are a multi-component combination of a metal precursor and a suitable activator such as an alkylaluminum derivative (Eagan et al., 2019). Oligomerization can take place in one or two steps, and this will impact product distribution. A two-step process can achieve greater selectivity for the jet fraction. The one-step oligomerization process follows a Shulz-Flory distribution, similar to Fischer-Tropsch synthesis, while a two-step oligomerization process follows a Poisson distribution with a larger fraction in the jet range (Nicholas 2017). Although these are the most common types of oligomerization

other types of technologies exist. For example, Shell developed the Shell Higher Olefin (SHOP) Process in the 1970s, which gives a broad Schulz–Flory distribution of olefins but includes adjustment of the product distribution through consecutive isomerization and metathesis steps to produce the desired chain lengths (Nicholas 2017).

The final steps in any AtJ process are hydrogenation and fractionation, which are usually routine processes in most refineries. During hydrogenation or hydroprocessing, hydrogen is added to remove any double bonds (in olefins) to produce fully saturated hydrocarbons. There are typically no technical obstacles or challenges, and either Cobalt-molybdenum or Nickel-molybdenum catalysts are generally used. Fractionation is the separation of the liquid product into fuels such as naphtha, jet and diesel based on boiling point. Hydrocarbon molecules of different chain lengths are produced during the process of oligomerization, and these are separated during fractionation.

5.4.1 Production of alcohol

There is a variety of different ways to make alcohol.

5.4.1.1 Ethanol

Bio-ethanol, as a "conventional" or first-generation biofuel, is predominantly produced *via* fermentation of sugars or starch by varieties of the yeast *Saccharomyces cerevisiae*. It is a fully commercial process that has been optimised for sugar and starch feedstocks. It involves the direct utilization of sugars from sucrose or starch and fermenting them into ethanol. The ethanol is finally recovered from the broth. The microbe used in ethanol production typically contains the invertase enzyme needed to break disaccharide sucrose (derived from cane or sugar beet) down to its hexose monomers (fructose and glucose). For starch hydrolysis, externally sourced amylase enzymes are usually used, and this is the dominant route used in the US corn ethanol industry.

A more complex process is required to hydrolyze lignocellulosic carbohydrates to fermentable hexose and pentose monosaccharides. As discussed in more detail later, despite decades of research and development, the commercialization of cellulosic ethanol has been challenging from a technical and economic perspective.

Several other microbes are also able to produce alcohols. The so-called ABE process (Acetone, Butanol, and Ethanol) using Clostridia, including *Clostridium acetobutylicum*, *C. saccharobutylicum*, *C. beijerincki* and *C. saccharoperbutylacetonicum*. Alternative microorganisms have also been evaluated for ethanol production, such as *Zymomonas mobilis,* which is a rapidly fermenting ethanologenic bacterium, or

thermophilic bacteria that can operate at the higher temperatures typically used for enzymatic hydrolysis of cellulose.

An alternative route to making ethanol is via syngas fermentation. Some autotrophic microorganisms can use single-carbon compounds such as CO and CO2 and energy-rich compounds such as CO and H_2. These feedstocks are used as energy sources to produce various compounds, including ethanol, butanol, butanediol, acetic acid and other molecules. Some of these microorganisms include acetogenic bacteria such as *Clostridium ljungdahlii* and *Clostridium carboxidivorans* (Munasinghe & Khanal, 2010). This technology is being used by Lanzatech/Lanzajet to produce biojet fuel with the CO, CO2 and H_2 derived from a variety of sources, e.g., syngas from gasification of feedstocks such as biomass or MSW.

Lanzatech/Lanzajet is also known to use waste gases from steel production for fermentation and ethanol production. Multiple gases are produced in steel manufacturing, including carbon monoxide (CO), hydrogen (H2), carbon dioxide (CO2), hydrogen sulphide (H2S), and methane (CH4). Typically, the gases are cooled, cleaned, and injected into the fermentation vessel, and ethanol and other chemicals are produced as a byproduct of microbial growth. The Lanzatech process can utilize gas streams with a range of CO and H2 compositions to produce ethanol and chemicals such as 2,3-butanediol at high selectivities and yields. Lanzatech's proprietary microbes can also consume hydrogen-free CO-only gas streams due to the ability of the microbe to perform a biological water gas shift reaction. This reaction allows the bacteria to compensate for any deficiency in H2 in the input gas stream by catalyzing the release of hydrogen from water using the energy in CO. However, syngas cleanup is critical as toxic compounds, such as hydrogen cyanide (HCN), could be formed and inhibit ethanol production, as shown in the Ineos Bio facility in Vero Beach [18].

An important advantage of using a thermochemical/biochemical pathway for ethanol production, i.e., gasifying biomass and fermenting the syngas, is that all the carbon in the biomass can be available for conversion. This contrasts with the biochemical production of ethanol from biomass, where only the sugars (and mainly 6-carbon sugars such as glucose) can be used in the fermentation process to produce ethanol (Asimakopoulos et al., 2018). However, the lignin and hemicellulose are largely unused, and as this can amount to ~45% of the carbon in the feedstock, this reduces the yield from most biomass feedstocks.[19]

[18] https://www.biofuelsdigest.com/bdigest/2014/09/08/feedback-may-help-explain-ineos-bios-high-levels-of-hcn-gas/

[19] Some microbes and genetically modified yeasts can utilise 5-carbon sugars such as xylose

Some of the disadvantages of syngas fermentation for the production of ethanol include gas-liquid mass transfer limitations, low productivity and high production cost (Sun et al., 2019). However, ongoing research and development is investigating ways to overcome these challenges with approaches including novel and modified reactors, development of enhanced growth and low-cost media, development of genetically modified organisms and process control to improve productivity (Sun et al., 2019). Several plants producing ethanol from steel mill gas fermentation are in operation or are under construction, as summarised in Table 7.

Table 7. Projects for ethanol production from steel mill gases (E4tech (UK) Ltd, 2021).

Developer	Tech licensor	Location	Scale (million litres/yr)	Feedstock	Products	Status
Lanzatech + Shougang Group	Lanzatech	Hebei province, China	58	Steel mill gases	Ethanol	Operational since 2018
ArcelorMittal (Steelanol EU H2020 project)	Lanzatech	Ghent, Belgium	80	Blast furnace offgas	Ethanol	Under construction
Baowu Group, Lanzatech, Baosteel gases, Sinopec, Virgin Airline	Lanzatech	Shanghai, China	0.45	Waste gas from steel mill	Ethanol	Operational since 2017
Lanzatech– CSC - China Steel Cooperation	Lanzatech	Kaohsiung, Taiwan	127	Waste gas from steel mill	Ethanol	Operational since 2015
Lanzatech, Indian Oil Company (IOC)	Lanzatech	Panipat, India	40	Waste gas from steel mill	Ethanol	Announced
PNNL, Lanzatech, Imperium, Boeing	Lanzatech	US	0.01[11]	Waste gas from steel mill	Jet fuel	Operational since 2015

5.4.1.2 Butanol

Butanol is a four-carbon primary alcohol and has advantages for alcohol-to-jet production as it requires fewer process steps than ethanol and a lower cost of conversion (Geleynse, Brandt, Garcia-Perez, et al., 2018). The fermentation of sugars to butanol is based on the ABE process using *Clostridium acetobutylicum,* which operated commercially before WWII (Qureshi & Blaschek, 1999). While research is ongoing, it is currently not a commercial process. Challenges to using *Clostridium* sp. in an industrial setting are their relatively slow growth, susceptibility to bacteriophage attack/cell degeneration, as well as a requirement to maintain strictly anaerobic conditions (Weber et al., 2010).

However, alternative approaches have been developed by companies such as Gevo, using genetically engineered microbes to produce iso-butanol. This isomer has proven to be easier to produce in yeast and it is also more valuable as a biofuel feedstock as a result of having a branched carbon chain. At this

time, Gevo is currently commercializing an alcohol-to-jet process based on ethanol rather than iso-butanol.

5.4.1.3 Methanol

Methanol is currently produced from natural gas and coal [20]. However, for SAF production, the methanol must be produced from sustainable sources such as renewable natural gas, biomethane, gasification of biomass or municipal solid waste (MSW)[21]. It can also be produced via power-to-liquid technologies using CO2 capture and hydrogen from renewable electricity.

According to the Methanol Institute, more than 80 renewable methanol projects around the globe are projected to produce more than eight million metric tons (2.7 billion gallons or 10 billion liters) of e-methanol and bio-methanol per year by 2027 [22]. One facility that has been producing bio-methanol for years is the Enerkem facility in Edmonton, Alberta, Canada, using the gasification of municipal solid waste (MSW).

Methanol can be produced from syngas at temperatures of 200-300^{o}C and pressures of 3.5 MPa (de Klerk, 2020). The reaction equilibrium limits the maximum theoretical once-through conversion to between 55-75% (de Klerk, 2020). A ratio of 2-2.5 H2/CO is required for methanol synthesis (Galadima & Muraza, 2015). Various types of catalysts have been used, such as mixed oxide systems of alumina, magnesium oxide and other transition metal oxides (Galadima & Muraza, 2015). However, new technologies have used Cu-based catalysts with the main catalyst formulation Cu/ZnO and alumina as a structural promoter (de Klerk, 2020). As this catalyst is also active for the water-gas-shift reaction (CO + H2O ↔ CO2 + H2), it is possible to produce methanol from CO2 (de Klerk, 2020). While methanol synthesis from syngas is similar to Fischer-Tropsch, product recover and recycling of unconverted syngas is less complex (de Klerk, 2020).

[20] https://www.methanol.org/wp-content/uploads/2016/06/MThe Methanol Institute (MI) is tracking more than 80 renewable methanol projects around the globe that are projected to produce more than eight million metric tons (2.7 billion gallons or 10 billion liters) per year of e-methanol and bio-methanol by 2027. I-Combined-Slide-Deck-MDC-slides-Revised.pdf

[21] The Enerkem facility in Edmonton produces methanol in this way.

[22] https://www.methanol.org/renewable/

5.4.2 AtJ Companies – planned and under construction

The first commercial-scale alcohol-to-jet facility, the Lanzajet Freedom Pines facility in Georgia, is nearing completion and is expected to produce SAF in 2024. Several other projects have also been announced (Table 8), although this list is not comprehensive, as ongoing announcements are often made. Based on publicly available information, the majority of these projects will use ethanol as the starting feedstock. However, the source of ethanol varies and ranges from crop-based ethanol to cellulosic ethanol, ethanol from syngas fermentation, etc.

Table 8 List of companies/projects based on alcohol-to-jet technologies (not comprehensive) (based on information from Argus Media)

Project name	Location	Capacity (t/yr)	Capacity (ML/Y)	Status
AtmosFUEL (Lanzajet, Carbon Engineering)	United Kingdom	76000	95.0	planned
Blue blade Energy		387000	483.8	Planned
Byogy	Kawasaki, Japan	22713	28.4	planned
Cosmo Oil/Mitsui	Japan	172000	215.0	planned
Flite		29000	36.3	planned
Gevo Net Zero 1	Lake Preston, South Dakota	158000	197.5	Planned
Gevo,	Silsbee, Texas	287	0.4	Planned
HCS Group	Speyer, Germany	60000	75.0	planned
Hyskies (Lanzatech, Vattenfall, SAS, Shell)	Forsmark, Sweden	86000	107.5	planned
Idemitsu	Chiba, Japan	76000	95.0	planned
Jet Zero Australia/Lanzajet	Queensland, Eastern Australia	76000	95.0	planned
Lanzajet	Japan	30000	37.5	planned
Lanzajet	Soperton, Georgia	29000	36.3	Planned
Lanzajet/Marquis	Hennepin, Illinois	345000	431.3	Planned
Lotus (SkyNRG, Lanzajet)	Pacific Northwest	14000	17.5	Planned
Project Dragon (Lanzajet)	Port Talbot, South Wales, UK	86000	107.5	planned
Renewable bio	Esperance, Western Australia	30000	37.5	planned
Speedbird (BA, Lanzajet, Nova Pangaea)	Wilton International, Teeside, UK	86000	107.5	planned
Summit Agricultural Group	US Gulf Coast	316000	395.0	Planned
Swedish Biofuels/COWI	Stockholm, Sweden	20000	25.0	planned

5.4.3 Alcohol-to-jet conversion technologies

Several technology providers offer an integrated ethanol-to-jet technology for licensing, e.g., Honeywell UOP, Axens and Lummus. The technology used by Lanzajet was originally developed by PNNL and licensed by Lanzatech. These technologies all use the basic process outlined earlier, where ethanol is dehydrated into ethylene and converted to butene and other intermediates before oligomerization into long-chain hydrocarbons.

More recent developments include the direct conversion of ethanol into butene, effectively bypassing the initial dehydration step. PNNL is pursuing this technology using Cu—ZrO2/SiO2 catalyst (copper-zirconia-based catalyst supported on silica), which uses an aldol condensation mechanism that does not produce CO2 (Dagle, 2023).

Mobil commercialized the conversion of methanol into hydrocarbons in the 1970s with their methanol-to-gasoline process (MTG). A similar methanol-to-olefins (MTO) technology was developed by researchers at Union Carbide that later became part of the UOP and Norsk joint venture (Gogate, 2019). Several other companies have developed similar types of technology, such as Lurgi's methanol-to-propylene (MTP) process.

Although the conversion of methanol into hydrocarbons has been carried out at a commercial scale, it has mainly been used for the production of short-chain olefins (for use in the chemical industry) or gasoline with catalysts and process conditions optimized for these products. For gasoline production, an important attribute in fuel chemistry is the benefits of a high-octane rating, which can be provided by the presence of aromatics. However, this is undesirable for SAF production.

The Mobil MTG process used an acidic HZSM-5 (zeolite) catalyst, while the Union Carbide researchers developed a novel SAPO-34 (silicoaluminophosphate) catalyst that allowed shape selectivity and control for the production of light olefins (C2-C4). In order to produce distillates, Mobil developed a further process step called the Olefins-to-gasoline/diesel (MOGD) process (Keil, 1999). The combination of the MTO and MOGD process is the basis of the current methanol-to-jet technologies. The three companies discussed here, ExxonMobil, Honeywell/UOP, and Topsoe, have operated commercial methanol conversion facilities, albeit for different purposes.

The basic process is essentially the same – methanol is converted to dimethyl ether (DME) and light olefins, which are further converted into longer-chain hydrocarbons through an oligomerization process (Ruokonen et al., 2021) (essentially the same as olefin oligomerization for the ethanol-to-jet process). Hydrogenation and fractionation are the final steps.

Although methanol conversion to jet fuel is not currently approved under ASTM D7566, a subcommittee has been assessing this pathway for approval. Samples from all three technology providers have been used in this analysis. Three main technology providers are offering integrated options for methanol-to-jet conversion: ExxonMobil, Honeywell-UOP, and Topsoe.

5.4.4 Swedish Biofuels process

The Swedish Biofuels process (Figure 10) produces paraffinics and aromatics in two separate process streams before blending.

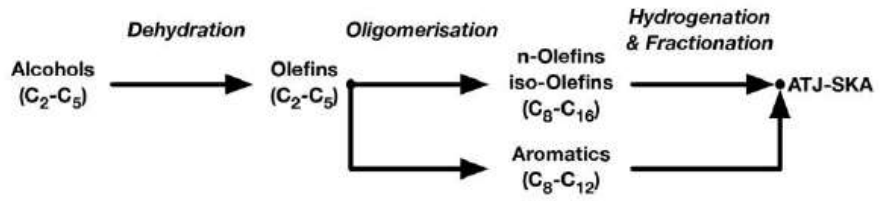


Figure 10 Illustration of the Swedish Biofuels AtJ technology

The Swedish Biofuels process can use any C2-C5 alcohol (ethanol, propanol, butanol, pentanol) as a mixture or as a single alcohol as a starting material. In the first step of the Swedish Biofuels AtJ process, the individual alcohols or their mixtures are dehydrated to a mixture of the corresponding olefins, which are, in subsequent stages, oligomerized to higher olefins. The higher olefins are then condensed into higher unsaturated compounds using two process streams, one producing n-olefins and iso-olefins, the other producing aromatics.

5.4.5 Availability of cellulosic ethanol will be a critical challenge to low CI SAF from ethanol

Global ethanol production is currently over 100 billion litres/yr, and its use has played a significant role in reducing transportation emissions. However, ethanol production has been primarily based on corn and sugar cane feedstocks that result in limited carbon reductions, primarily due to the inputs required for crop cultivation. Also, from a sustainability perspective, the use of food crops is problematic because of concerns about food vs. fuels.

Consequently, it has been suggested that “advanced biofuels” based on lignocellulosic residues can deliver fuels with a lower carbon intensity. Biomass feedstocks sequester carbon from the atmosphere and should also be available in much greater quantities. However, producing cellulosic ethanol is a complex process, and the key steps involved in cellulosic ethanol production are summarised in Figure 11.

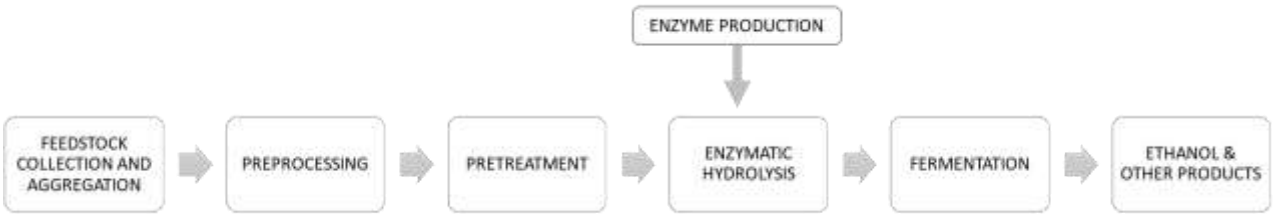


Figure 11 Process flow chart of key steps in cellulosic ethanol production

Cellulosic ethanol has been the subject of intensive research ever since the oil crisis of the 1970s. Although several pioneer biorefineries were built and operated in the 2000s, most of these facilities never produced any significant volumes of cellulosic ethanol and none of the facilities ever reached their design capacity. While cellulosic ethanol production involves several complex, multi-component stages, the main challenge for these pioneer facilities involved the collection, storage and processing of the biomass feedstocks. For example, storage of agricultural residue bales often resulted in degradation and loss of sugars, reducing final ethanol yields. Other examples include the self-combustion of bales, which proved very difficult to extinguish. Typically, assessing feedstock quality at the refinery gate was poor and quite inconsistent, and issues such as high contaminants caused problems with equipment and processing.

The challenges of commercializing cellulosic ethanol have also been highlighted by the closure of the Clariant facility in Romania in December 2023[23]. Although the facility started operations in 2021, it never attained full capacity. However, efforts to scale up production of cellulosic ethanol are ongoing with Raizen, in Brazil, producing cellulosic ethanol from bagasse and announcing plans for several new facilities [24]. In India, Praj is also continuing efforts to commercialize its cellulosic ethanol technology. However, it is likely that the availability of cellulosic ethanol via the biochemical conversion of agricultural residues and other wastes will remain challenging.

[23] https://www.reuters.com/business/clariant-cut-170-jobs-after-closing-romania-plant-downsize-german-operations-2023-12-06/

[24] https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/shell-and-raizen-sign-large-cellulosic-ethanol-deal.html

5.4.6 Carbon intensity of AtJ pathways

CORSIA provides default LCA values for the alcohol-to-jet process pathways, with Table 9 showing the values for ethanol-to-jet. Although the default values for corn ethanol do not provide any emissions reductions, companies can use the CORSIA life cycle methodology to demonstrate that they can achieve a lower carbon intensity. It is worth noting that sugarcane ethanol to jet can provide lower carbon intensity SAF than a standalone conversion using agricultural residues as a feedstock.

Table 9 CORSIA Default Life Cycle Emissions values for ethanol-to-jet conversion processes

Region	Fuel Feedstock	Pathway Specifications	Core LCA Value	ILUC LCA Value	LS_f (gCO_2e/MJ)
Brazil	Sugarcane	Integrated conversion design	24.1	8.7	32.8
Global	Sugarcane	Integrated conversion design	24.1	8.5	32.6
USA	Corn grain	Standalone or integrated conversion design	65.7	25.1	90.8
Global	Corn grain	Standalone or integrated conversion design	65.7	34.9	100.6
Global	Agricultural residues	Standalone conversion design Residue removal does not necessitate additional nutrient replacement on the primary crop.	39.7	0	39.7
Global	Agricultural residues	Integrated conversion design Residue removal does not necessitate additional nutrient replacement on the primary crop.	24.6	0	24.6
Global	Forestry residues	Standalone conversion design	40.0	0	40.0
Global	Forestry residues	Integrated conversion design	24.9	0	24.9
USA	Miscanthus (herbaceous energy crops)	Standalone conversion design	43.3	-42.6	0.7
EU	Miscanthus (herbaceous energy crops)	Standalone conversion design	43.3	-23.3	20.0
Global	Miscanthus (herbaceous energy crops)	Standalone conversion design	43.3	-19.0	24.3
USA	Miscanthus (herbaceous energy crops)	Integrated conversion design	28.3	-42.6	-14.3
EU	Miscanthus (herbaceous energy crops)	Integrated conversion design	28.3	-23.3	5.0
Global	Miscanthus (herbaceous energy crops)	Integrated conversion design	28.3	-19.0	9.3
USA	Switchgrass (herbaceous energy crops)	Standalone conversion design	43.9	-10.7	33.2
Global	Switchgrass (herbaceous energy crops)	Standalone conversion design	43.9	4.8	48.7
USA	Switchgrass (herbaceous energy crops)	Integrated conversion design	28.9	-10.7	18.2
Global	Switchgrass (herbaceous energy crops)	Integrated conversion design	28.9	4.8	33.7
Global	Waste gases	Ethanol produced via microbiologic conversion route Standalone conversion design	42.4	0	42.4
Global	Waste gases	Ethanol produced via microbiologic conversion route Integrated conversion design	29.4	0	29.4

5.5 Power-to-liquids

The basic power-to-jet process (Figure 12) involves hydrogen produced through the electrolysis of water and CO2 based on direct air capture or using CO2 from a concentrated source such as waste gases. Synthesis of hydrocarbons, including jet, can proceed through Fischer-Tropsch and can also take place via a methanol intermediate. As CO is required, CO2 is converted into CO through a reverse water-gas-shift reaction (RWGS). Although individual processes in the PtL pathway are at TRL 8-9, the RWGS process is still at a low TRL level (6). Thus, it will impact the overall TRL level of the integrated process.

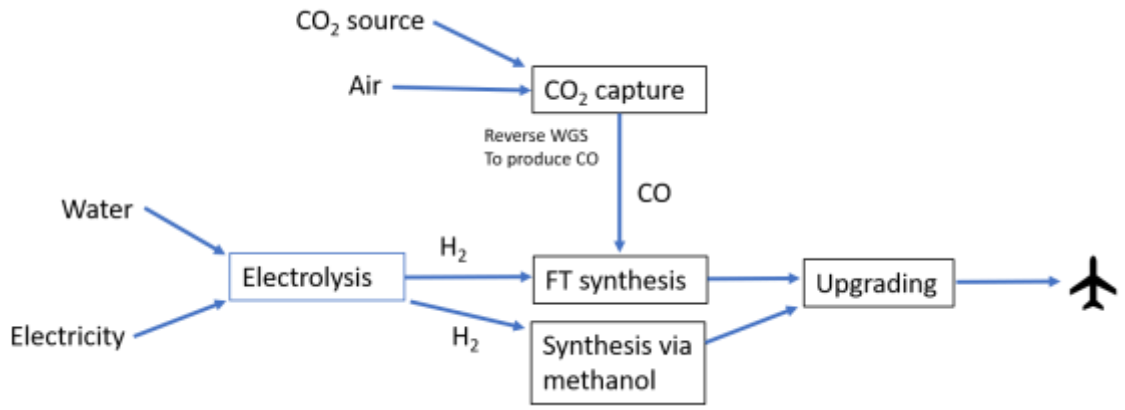


Figure 12 Simplified illustration of the power-to-liquid process for the production of aviation fuels

5.5.1 Companies developing PtL technologies

A list of planned projects/companies developing PtL technologies is shown in Table 10.

Table 10 List of companies/projects that focus on SAF production through the power-to-liquids pathway (not comprehensive) (Source Argus Media)

Company name	Location	Capacity (t/yr)	Capacity (ML/Y)	Status
SAF+ Consortium	Quebec, Canada	23000	28.8	Planned
Dimensional Energy	Tuscon, Arizona	1	0.0	Planned
Dimensional Energy/Heliogen	Lancaster, California	5	0.01	Planned
HIF Global	Texas	485000	606.3	Planned
Shell	Louisiana	434000	542.5	Planned
Arcadia eFuels	Vordingborg, Zeeland, Denmakr	55000	68.8	planned
Porsgrunn (Nordic electrofuel)	Norway	8000	10.0	planned
E-Alto (Velocys)	Immingham, UK			planned
IdunnH2	Helguvik Harbour, Iceland	65000	81.3	planned
Engie/Infinium	Dunkirk, France			planned
HyNovera (Hy2Gen)	Gurdanne, France	16000	20.0	planned
P2X-Europe	Figueira da Foz, Protugal	40000	50.0	planned

Synhelion	Spain	760	1.0	planned
Zenid (SkyNRG, Hague Airport, Climeworks)	Rotterdam	280	0.4	planned
Synkero	Amsterdam	50000	62.5	planned
Hykero	Bohlen-Lippendorf, Saxony	50000	62.5	planned
Hy2Gen (Green Areal Lausitz)	Janschwalde, Brandenburg			planned
Ineratec/Safran/Engie	Frankfurt	3500	4.4	planned
Synhelion	Julich, Germany	8	0.01	planned
P2X-Europe	Hamburg, Germany	200	0.3	planned
CEMEX/SASOL	Rudersdorf			planned
Westkuste 100	Schleswig-Holstein			planned
Green Fuels Hamburg	Hamburg, Germany	10000	12.5	planned
SkyNRG/Stuttgart Airport/Scwenk Zement	Heidenheim-Mergelstetten, Germany	50000	62.5	planned
Shell	Wesseling, Germany	100000	125.0	planned
Atmosfair	Werlte, Germany	365	0.5	operational
			2281.4	

5.5.2 Fischer-Tropsch pathway

The Fischer-Tropsch pathway is fully commercial and has been widely used for decades based on the gasification of coal. The FT process uses syngas (CO and H2) to synthesize long-chain hydrocarbon molecules. In the case of power-to-liquids, the source of carbon is CO2, which must be converted to CO using the Reverse Water Gas Shift Reaction to produce syngas. Another option is the direct conversion of CO2 with H2 into hydrocarbons. However, this approach is challenging and requires a catalyst, such as Fe, that can convert the CO2 to CO while also carrying out the FT synthesis (Panzone et al., 2020).

5.5.3 Methanol pathway

Methanol has been conventionally produced at an industrial scale from syngas (a combination of H2, CO, and CO2) derived from the gasification of coal or natural gas. During methanol production, other coproducts are formed, and according to Marlin, the subsequent energy and costs in conventional methanol plants are based on separating these coproducts and purifying the methanol (Marlin et al., 2018). However, the production of methanol using captured CO2 and renewable hydrogen simplifies the process as the sources are pure, and the concentrations of the reactants can be controlled.

When methanol production proceeds from CO, the reaction is very exothermic, and the removal of heat is important in the process and reactor design. Alternatively, methanol synthesis from pure CO2 is less exothermic and can use a modified, simpler process and reactor configuration that has a lower cost and

higher efficiency (Marlin et al., 2018). Conversion of captured CO2 to methanol has been carried out at an industrial scale by Carbon Recycling International in Iceland [25].

Azhari has also suggested that producing methanol directly from CO2 has economic and environmental benefits. However, these workers state that the CO2 to methanol reaction is kinetically limited to 15-25% conversion and requires high energy input due to the stability of the CO2 molecule (compared to CO) (Azhari et al., 2022). Although undesired CO formation can occur due to the RWGS reaction, the reaction conditions that limit the RWGS reaction result in a lower selectivity for methanol. However, CO2 conversion to methanol produces water as a byproduct, which can cause deactivation of the catalyst. Therefore, these workers argue that several challenges still remain to obtain high CO2 conversion and high methanol selectivity (Azhari et al., 2022 and that the development of new, more efficient catalysts could potentially address these challenges. Currently, the conversion of CO2 to methanol uses Cu-ZnO-Al2O3 catalysts. However, copper materials are being extensively investigated for CO2 conversion to methanol, with the choice of the catalyst support material improving conversion and selectivity. For example, a ZrO2 support material can substantially increase the selectivity to methanol. Other catalysts under investigation include cobalt-based systems (on a silica support (Wang et al., 2020) and precious metal catalysts such as Au, Pd, and Pt (Azhari et al., 2022).

While methanol has been the main alcohol targeted for synthesis, higher alcohols such as ethanol could potentially have advantages. However, although the conversion of CO2 into ethanol with high selectivity is difficult and is usually lower than 16% (Panzone et al., 2020), the active investigation of highly selective catalysts is ongoing (Panzone et al., 2020).

The selection of the methanol route for the PtL process has some advantages over the FT pathway. For example, the intermediate storage of syngas or hydrogen is complex, while liquid methanol is easily stored and transported. When using intermittent renewable power, methanol storage can act as a "buffer" between variable power and the need for continuous operation in the downstream synthesis process (E4Tech, 2021).

5.5.4 Carbon source

Carbon for the PtL process can be captured directly from the air (direct air capture, DAC) and point sources such as flue gas from industrial plants, biogas, and bio-based ethanol production. However, the concentration of CO2 can vary substantially in various sources: air contains 0.04% of CO2 by volume,

[25] https://www.carbonrecycling.is/

biogas 20-45% and flue gases from cement plants 14-33% (PtL Roadmap Sustainable Aviation Fuel from Renewable Energy Sources for Aviation in Germany, n.d.).

There are also substantial differences between the various carbon capture technologies, which, together with the source of CO2, impact the cost of carbon. According to McKinsey, industrial point-source capture could cost as little as $25 per tonne of CO2 in some industries, such as bioethanol, and more than $100 in sectors, such as cement production (McKinsey, 2022). Direct air capture (DAC), on the other hand, costs about $250-$600 per tonne of CO2, with differences based on whether a liquid solvent is used ($170-$260/tonne CO2), or solid sorbent ($270-$500/tonne of CO2) (McKinsey, 2022). Although DAC using solid sorbent is at a lower TRL level and requires further development, it has a greater potential for cost reduction while also operating at much lower temperatures and requiring lower energy inputs (McKinsey, 2022).

Capturing CO2 from biogenic sources can have significant benefits from a sustainability perspective. However, the decentralized nature of biogenic CO2 sources has been identified as a challenge for large-scale applications of PtL, as it is likely that transporting the captured CO2 to a centralized PtL facility will be required. In the US, a number of companies are pursuing pipeline projects in the Midwest to transport the CO2 captured at ethanol plants. However, permits for proposed projects by Iowa-based Summit Carbon Solutions and Nebraska-based Navigator CO2 Ventures were rejected in 2023 due to public concern, risks and environmental impacts [26]. Other companies include Wolf Carbon Solutions and Tallgrass Energy. While over 5000 miles of CO2 pipelines exist in the US, their primary purpose is to transport CO2 to oil fields for enhanced oil recovery (Parfomak, 2023).

5.5.5 Electrolysis technologies

The majority of commercial electrolysis technologies available today are alkaline water electrolysis (AWE) and proton exchange membrane electrolysis (PEM) plants. Although the solid oxide electrolyzer cell (SOEC) technology offers an advantage over the other technologies, it is at a much lower TRL level (TRL 6). However, co-electrolysis through SOEC can produce syngas without a separate reverse water gas shift step and save on CAPEX costs (McKinsey, 2022). The SOEC process can also use waste heat to reduce electricity needs and overall production costs by about 20% (McKinsey, 2022). However, excess on-site heat must be available to access this benefit. While SOEC technology also requires a more stable supply of renewable electricity (McKinsey, 2022), it is considered a suitable technology for PtL using

[26] https://www.reuters.com/sustainability/us-carbon-capture-pipeline-setbacks-reflect-challenges-climate-fight-2023-09-28/

industrial CO2 (Marchese et al., 2020). The company Sunfire[27] is commercializing SOEC technology for freestanding hydrogen production or co-electrolysis for syngas production.

5.5.6 Reverse Water Gas Shift Reaction

The Reverse Water Gas Shift (RWGS) reaction converts CO2 into CO and water using hydrogen, and it is currently used to produce syngas based on CO2. Although the RWGS technology is not yet at a commercial level, several companies are involved in advancing this technology [28](IFPEN/Axens, hte-company, Topsoe, Shell, etc.).

Various catalysts can be used for the RWGS reaction, including Pt, Pd, Rh, Ru, Au, Fe, Mo, Cu, Co and Ni-based catalysts, which are typically supported on metal oxides. While noble metals have a very high hydrogenation activity, their high cost has hindered industrial application. Although Cu- and Ni-oxides have a lower price, high activity and selectivity, they tend to become deactivated in RWGS (Bown et al., 2021). Consequently, ongoing research and development are focused on overcoming problems with these catalysts and the development of alternative catalysts based on Mo, Co, and Fe. Catalysts that are able to suppress CO2 methanation will be preferable as methanation is undesirable (Bown et al., 2021).

5.5.7 Cost of PtL

As shown in Figure 16, SAF production through the PtL process has a very high minimum fuel selling price compared to most other SAF technologies. For example, $4.02/L for DAC in a pioneer facility ($3.60/L for an nth facility), while CO2 from flue gas can give PtL at $3.14/L for a pioneer facility ($2.70/L for an nth facility) (Brandt, Tanzil, et al., 2021a). In related techno-economic analyses, Schmidt et al. (2018) calculated that a minimum fuel selling price for aviation fuel from PtL, based on direct air capture, would be USD4974/MT, based on a concentrated CO2 source at USD3829/MT. A comprehensive review of production costs by Brynolf et al. (2018) indicated a cost range of EUR200-280_{2015}/Mwh_{fuel} (Brynolf et al., 2018). According to McKinsey, the fuel synthesis process in PtL represents only 12% of the cost, while

[27] https://www.sunfire.de/en/

[28] https://www.hte-company.com/en/industries/co2sday/rwgs; https://ineratec.ch/en/technology/: https://www.shell.com/business-customers/catalysts-technologies/resources-library/shell-man-energy-solutions-pilot-plant-development-rwgs-technology.html; https://www.ifpenergiesnouvelles.com/article/e-fuels-axens-paul-wurth-sms-group-and-ifpen-sign-agreement-co-development-reverse-water-gas-shift-technology; https://www.topsoe.com/our-resources/knowledge/our-products/equipment/e-react-fuels

renewable electricity, hydrogen, and carbon inputs will account for more than three-quarters of the cost by 2030 (McKinsey, 2022). Renewable electricity accounts for about 25%, hydrogen capital costs about 30% and carbon capture about 15-30%, depending on the source of CO2 (McKinsey, 2022).

Other work has suggested that the electrolyzer and electricity costs (including capacity factors (CFs)[29] and cost for hydrogen storage) have the biggest impact on the cost of eFuels (Grahn et al., 2022). Also, when "green" electricity is intermittent, hydrogen storage may be needed to enable stable fuel production.

5.5.8 Electricity demand for PtL

According to McKinsey, at least 36 MWh is needed to produce 1 tonne of efuel (kerosene plus other products) that is produced via PtL. When using direct air capture, this increases to 45-52 MWh per tonne (McKinsey, 2022), with high-temperature DAC using more electricity. As illustrated in the McKinsey report, the production of 50,000 tonnes of PtL fuel (~60 million litres) will require 1.1 TWh of electricity, which is equivalent to more than 2,700 acres of photovoltaics (McKinsey, 2022). It should also be noted that efuels represent an inefficient use of electricity (only 10-15%) compared to electric vehicles, which have an efficiency of 80% (Kohl, 2022). Consequently, some workers argue that efuels are therefore an inefficient way of using energy and that this energy could perhaps be directed to other sectors where greater emissions reductions could be achieved.

5.5.9 Opportunities and challenges of SAF through PtL

Commercialization of the power-to-liquids process still has some technical challenges pertaining to individual processes such as the RWGS reaction and SOEC electrolysis. This is also a costly pathway for the production of SAF. Consequently, the main targets of cost reduction are reducing the cost of renewable electricity, reducing the cost of electrolyzers and reducing the cost of direct air capture (McKinsey, 2022).

[29] the ratio between the actual output of unit versus what it is capable of producing at maximum output

5.6 Co-processing in conventional refineries

A number of refineries in Europe have been producing lower carbon-intensive jet (LCIJ) fuels through co-processing, and several additional companies have announced plans for coprocessing (Table 11). Coprocessing of lipids is approved under ASTM D1655 but is limited to the insertion of 5% biobased intermediates, limited to lipids and Fischer-Tropsch liquids. Although a subcommittee under ASTM is exploring the possibility of expanding this blending limit to 30%, this has not been finalized. The companies listed in Table 11 co-process lipids, while there is only one refinery, Marathon Petroleum refining, that co-process Fischer-Tropsch liquid from Fulcrum Bioenergy. However, there has been no public information to indicate whether SAF volumes are produced. While co-processing of pyrolysis and HTL biocrudes is being pursued, this has not been approved under ASTM. Many technical challenges have to be resolved before co-processing of biocrudes is commercial.

Table 11 Companies engaged in SAF production through coprocessing, operational and planned (capacity not available) (Source: Argus Media)

Company name	Location	Technology	Capacity (t/yr)	Capacity (ML/Y)	Status
Phillips 66	Humber, UK	Co-processing			operational
TotalEnergies	Normandy	Co-processing			operational
BP	Lingen, Germany	Co-processing			operational
OMV	Schwechat, Austria	Co-processing			operational
OMV	Petrobrazi, Romania	Co-processing			operational
ENI	Taranto, Italy	Co-processing			operational
Repsol	Tarragona, Spain	Co-processing			operational
BP	Castellon, Spain	Co-processing			operational
Repsol	Teronor, Spain	Co-processing			operational
Repsol	Puertollano, Spain	Co-processing			operational
Cosmo Oil	Sakai, Japan	co-processing	22713	28.4	planned
Repsol	Petronor, Bilbao, Spain	co-processing			planned
Tupras	Izir, Turkey	co-processing	300000	375.0	planned

5.7 Pyrolysis, catalytic pyrolysis, hydrothermal liquefaction with upgrading

Although ongoing research and development is underway for the development of SAF via HTL of wet wastes such as sewage sludge, this technology is still at lower TRL levels. Wet waste is a very low-cost feedstock, and studies have shown that upgraded material within the jet range exhibits key fuel properties. This suggests that it could be a promising candidate feedstock for the production of SAF (Cronin et al., 2022). However, it was found that, after upgrading, the wet waste HTL biocrude still contained high levels of nitrogen that would require further denitrogenation (Cronin et al., 2022).

A company that has attracted significant attention is Alder Renewables (previously Alder Fuels), which made headlines in 2021 [30] when United and Honeywell announced they were investing in Alder. United has agreed to purchase 1.5 billion gallons of sustainable aviation fuel (SAF) from Alder over a period of 20 years.

The Alder technology is based on the BTG fast pyrolysis process but combines Alder's proprietary technology to produce advanced renewable crudes (ARC) (Figure 13). Much of the technology development is carried out by NREL[31] , and the completion of a pilot skid was announced in 2023[32]. As the technology is still at a low TRL level, significant development and upscaling is in progress.

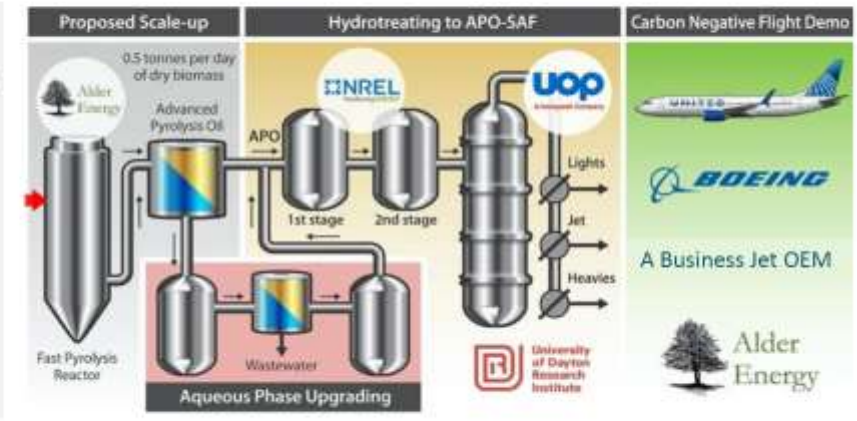


Figure 13 Illustrated process for Alder Renewables technology

6. Price of SAF, production cost and techno-economic analyses

The likely production costs of making SAF via various technologies and feedstocks involve calculations based on techno-economic analyses using a net present value (NPV) of zero. Most of the data is based on techno-economic analyses carried out by Washington State University as part of this group's work in the US Federal Aviation Administration Center of Excellence for Alternative Jet Fuels and Environment (ASCENT). The assumptions are available as open-access spreadsheets Brandt et al., 2023; Brandt,

[30] https://www.honeywell.com/us/en/press/2021/09/united-honeywell-invest-in-new-clean-tech-venture-from-alder-fuels-powering-biggest-sustainable-fuel-agreement-in-aviation-history
[31] https://www.nrel.gov/news/program/2022/enroute-to-market-alder-fuels-and-nrel-partner-to-scale-sustainable-aviation-fuel-technology-for-commercial-use.html
[32] https://www.alderrenewables.com/latest-news-research/next-step-in-alders-commercialization-journey-now-underway-introducing-pioneer-full-time-skid-operations

Geleynse, et al., 2021; Brandt, Tanzil, et al., 2021b, 2021a; Brandt & Wolcott, 2021; Eswaran et al., 2021; Geleynse, Brandt, Garcia-Perez, et al., 2018).

However, although the current price at which SAF is sold today is described, publicly available information is not readily available. Consequently, we have relied on Argus Media and S&P Global Platts price assessment. In a media release by Argus Media on 27 January 2023, SAF prices were as high as USD$3,400 per ton (Argus Media, 2023). However, the price of SAF can be 3-6 times higher than the price of "conventional" jet fuel, the market price is influenced by factors such as the availability of SAF, while techno-economic analyses calculate production costs as a way of facilitating comparisons based on common assumptions. A comparison between total capital investment (TCI) for pioneer and nth facilities for different technologies and the likely minimum selling price (MSP) for the SAF produced via each of these routes is summarised in Table 12 (Brandt et al., 2023; Brandt, Geleynse, et al., 2021; Brandt, Tanzil, et al., 2021b, 2021a; Brandt & Wolcott, 2021).

It is apparent that there are substantial differences in the amount of SAF produced by the different technologies, with FT delivering 40% of the total liquid fraction as SAF while ATJ can deliver a 70% SAF fraction (or up to 90% as claimed by Lanzajet). The remaining products are diesel, gasoline, and lights, depending on the technology used.

The scale of facilities can vary substantially between technologies when considering the construction of the nth plant. Although ATJ and HEFA nth facilities, which use easily transported liquid feedstock, can potentially be as large as 1 billion litres per year, in contrast, gasification facilities are likely to be much smaller due to the nature of the solid biomass feedstock logistics, their low energy density and the low yields that can be achieved.

Table 12 Techno-economic analysis of the various technologies and feedstocks based on pioneer and nth facilities. Feedstock costs are for preprocessed feedstocks except for HEFA. GFT = gasification with Fischer Tropsch. As HEFA-based processes are considered to be already commercial, data for pioneer facilities were excluded. GFT=gasification and Fischer-Tropsch; ATJ=alcohol-to-jet; PtL=power-to-liquids

Processing technology	Feedstock	Feedstock cost (USD$/tonne)	Yield*	Product slate (%) (jet:diesel:gasoline:other)	TCI (million USD$)		MSP SAF (USD$/L)	
					Nth (total distillate MLPY)	Pioneer (total distillate MLPY)	Nth	pioneer
GFT	MSW	30	0.31	40:40:20	1427.6 (500)	2944 (500)	0.9	1.63
GFT	Forest residues	125	0.18		1207.2 (300)	2488.7 (300)	1.69	3.3
GFT	Agricultural residues	110	0.14		1123.8 (220)	2316.8 (220)	2.0	3.8
ATJ	Ethanol (based on corn)	456	0.60	70:0:30	316.4 (1000)	662 (1000)	0.79	0.87
ATJ	Isobutanol	1110	0.75		649.5 (1000)	1349.8 (1258)	2.35	2.49
HEFA	FOGs	580	0.83	55:26:19	447.7 (1000)		0.8	
HEFA	Vegetable oil	810	0.83		456.4 (1000)		1.1	
Pyrolysis	Forest residues	125	0.28	44:28:16:12	384.4 (134)	794.7 (134)	1.3	2.04
Pyrolysis	Agricultural residues	110	0.27		384.4 (134)	794.7 (134)	1.33	2.08
PtL	DAC CO_2	300	0.24	40:40:20	1313.2(400)	2266.1 (400)	3.60	4.02
PtL	Flue gas CO_2	50	0.24		1248.7 (400)	2155.9 (400)	2.70	3.14

*(wt total distillate/wt dry feedstock, except in the case of pyrolysis which is L/kg)

Links to open-access models where data was sourced:

ATJ: https://doi.org/10.7273/000001461

FT: https://doi.org/10.7273/000001459 (includes PtL)

FT feedstock pre-processing: https://doi.org/10.7273/000001463

HEFA: https://doi.org/10.7273/000001460

Pyrolysis: https://doi.org/10.7273/000002563

(Brandt et al., 2023; Brandt, Geleynse, et al., 2021; Brandt, Tanzil, et al., 2021b, 2021a; Brandt & Wolcott, 2021)

A graphical comparison of the total capital investment (Figure 14) and total capital investment per 100 million litres of total product (Figure 15) shows the significant capital investment (CAPEX) required for power-to-liquid and gasification facilities compared with other technologies.

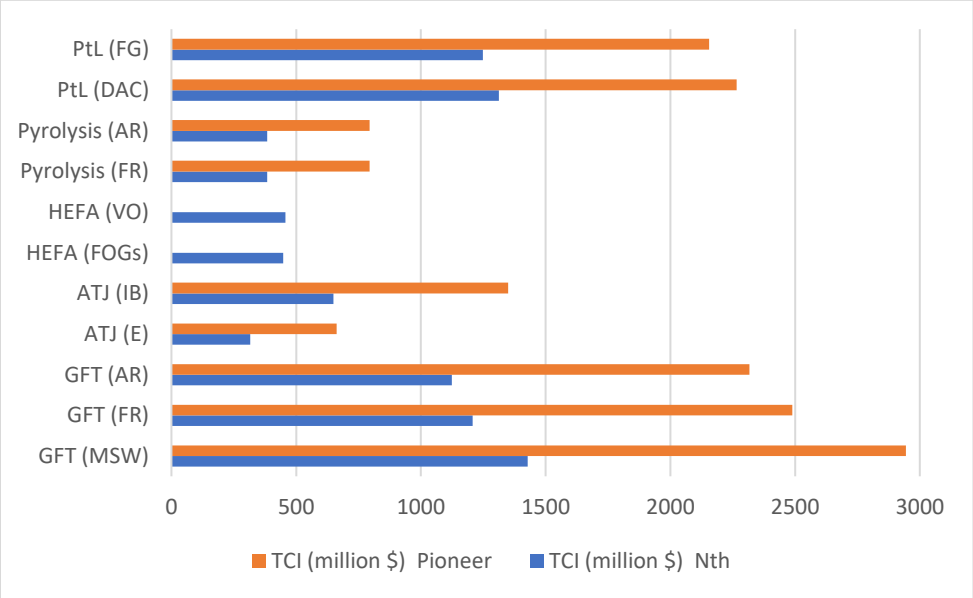


Figure 14 Total Capital Investment (TCI) in USD^{2017} for Pioneer and Nth facilities based on technology/feedstock combinations. Note that facility size varies significantly (See Table 12). FG=flue gas; DAC=direct air capture; AR=agricultural residues; FR=forest residues; VO=vegetable oil; FOGS=fats, oils and greases; IB=isobutanol; E=ethanol; MSW=municipal solid waste (based on data in Table 2)

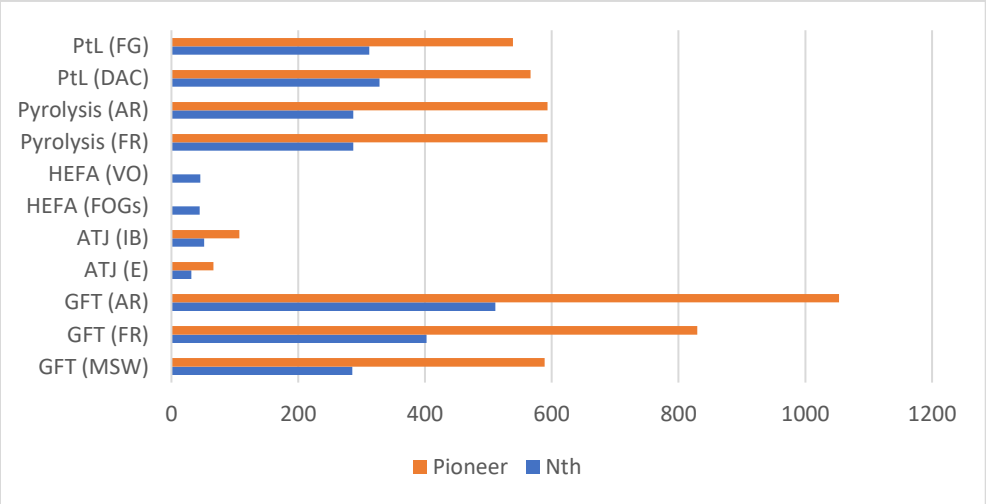


Figure 15 Total Capital Investment (TCI) in USD^{2017} per 100 million litre total product (not total SAF) for Pioneer and Nth facilities based on technology/feedstock combinations. (based on data in Table 2)

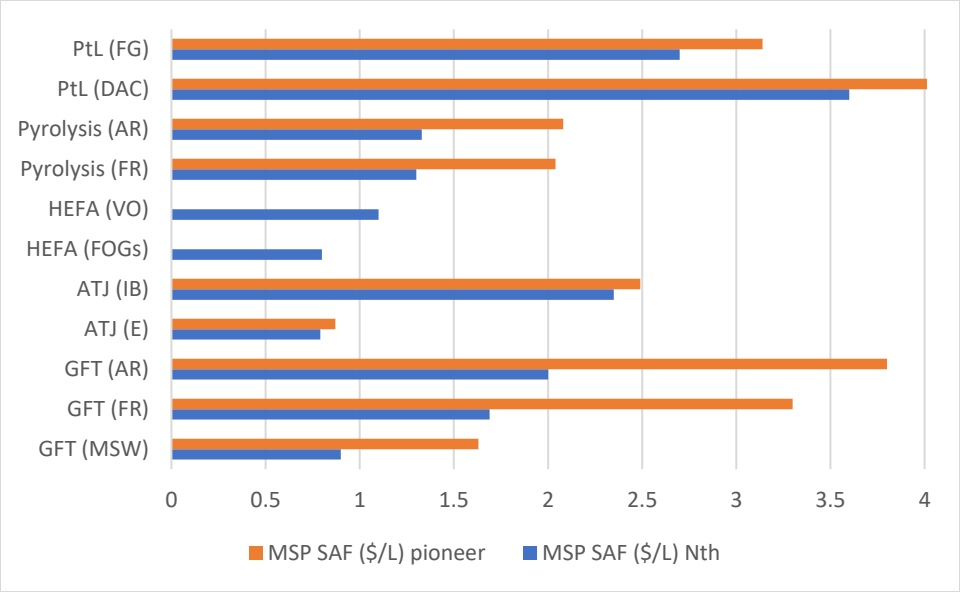


Figure 16 Comparison of minimum selling price for different technologies and feedstocks for pioneer and Nth facilities (based on data in Table 2)

When the minimum selling price for the different SAF-related technologies is compared (Figure 17), both the WEF-CST and ICF reports indicate that production costs for all SAF technologies will remain higher than conventional jet fuel until at least 2050 (Blanshard et al., 2021; McKinsey & Company, 2020). The projected cost reduction trends from 2020 to 2050, based on the WEF-CST report (Figure 17), indicate that it is likely that the high cost of SAF compared with conventional jet fuel will persist until 2050.

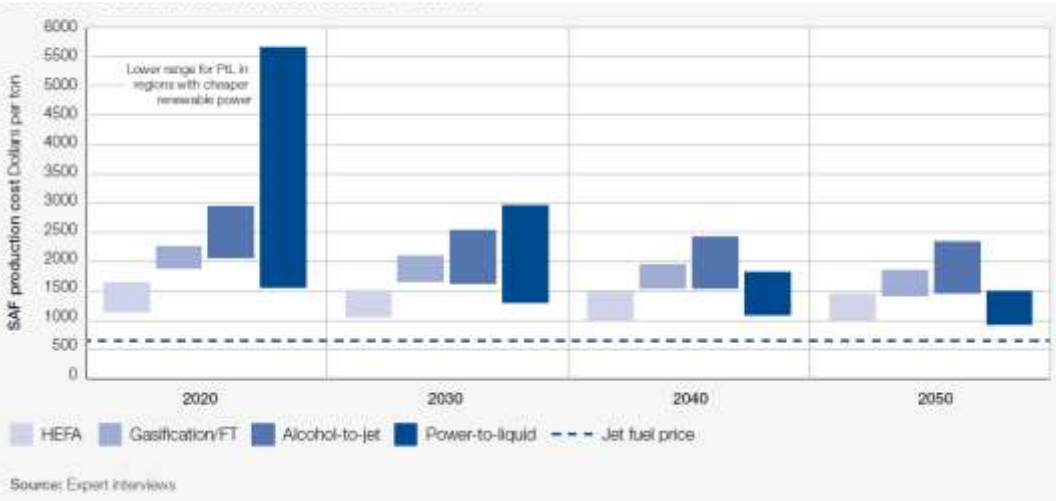


Figure 17 Global SAF production cost for selected technologies from the WEF-CST report (USD) (McKinsey & Company, 2020) AtJ in this report was limited to cellulosic ethanol.

Although production costs for all technologies are expected to improve over time due to learning, innovation and greater economies of scale, pioneer or first-of-kind facilities are expected to be about 50% more expensive to construct (de Jong et al., 2015)(de Jong et al., 2015)(de Jong et al., 2015)(de Jong et al., 2015)(de Jong et al., 2015). However, significant cost improvements will only be obtained if there is a move toward nth facilities, assuming multiple biorefineries based on the same technology. Before a pioneer facility is built, production costs are generally underestimated, with cost improvements typically occurring once the number of facilities based on a specific technology has increased in number (Maniatis et al., 2017). The production costs reported in various reports generally reflect the construction of the nth facility. However, as only the HEFA-to-SAF route is fully commercial, the reported production costs via other technologies have a high level of uncertainty.

It should be noted that different SAF production routes will show potential cost improvements in different areas. For example, the gasification and Fischer-Tropsch routes involve high construction costs and require significant CAPEX. Consequently, significant cost improvements are likely to be achieved for this component of the overall process. The production cost estimates for power-to-liquids (PtL) show the greatest potential for improvement over time, as the cost of hydrogen is expected to decrease significantly by 2050. Recent work has shown that the cost of hydrogen (from renewable electricity) has the most significant impact on the cost of PtL SAF (McKinsey & Company, 2020). As the feedstock is the largest component of the overall production costs of HEFA-derived-SAF, any reduction in feedstock costs will have the most impact on reducing the cost of any SAF produced.

7. ICAO CORSIA framework for sustainable aviation fuels

Although the primary motivation for developing lower carbon-intensity jet fuels is to reduce the carbon emissions of the aviation sector, this should also encompass the overall sustainability of SAF production and use. The International Civil Aviation Organisation (ICAO) developed a market-based mechanism in the form of the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) to regulate the obligation of airlines to purchase offsets above certain emission limits.

As SAF can be used in place of offsets, CORSIA has defined eligible fuels and developed sustainability criteria and a life cycle methodology for calculating the carbon reduction potential of eligible fuels. Two sustainability certification schemes have been approved by ICAO (International Civil Aviation

Organisation (ICAO), 2019a) to assess the sustainability of SAF, the Roundtable of Sustainable Biomaterials (RSB)[33] and the International Sustainability and Carbon Certification (ISCC)[34].

It should be noted that "sustainability" encompasses multiple criteria and principles, including the potential for carbon reduction, as calculated through a life cycle assessment (LCA). The entire supply chain, from feedstock harvesting to SAF production, is assessed against certain principles and criteria. However, this can differ between the LCA models used and the certification bodies carrying out the overall sustainability assessment. For example, the sustainability of the forest sector is assessed by bodies such as the Sustainable Forest Initiative (SFI)[35] and the Forest Stewardship Council (FSC)[36]. In parallel, the Sustainable Biomass Program (SBP)[37] assess the sustainability of forest/agriculture-based feedstocks to ensure that biomass is sourced from legal and sustainable sources.

A CORSIA-eligible fuel is defined as a "CORSIA sustainable aviation fuel or a CORSIA lower carbon aviation fuel, which an operator may use to reduce their offsetting requirements." Eligibility is determined based on meeting sustainability criteria, which includes minimum carbon intensity reductions (International Civil Aviation Organisation (ICAO), 2019b, 2021).

Default CI values are established for technology pathways based on different feedstocks and different regions. This is calculated as a CORE lifecycle value and an Induced Land Use Change (ILUC) value, which is summed together to determine the full lifecycle emissions value for the CORSIA-eligible fuel (International Civil Aviation Organisation ICAO), 2022). Although the actual CI can be determined using the CORSIA LCA methodology (International Civil Aviation Organisation (ICAO), 2019a), only the CORE value can be changed with the appropriate ILUC value used as a default. Comprehensive sustainability criteria were agreed upon in November 2021 at the ICAO level (International Civil Aviation Organisation (ICAO), 2019b, 2021), and currently, a minimum of 10% life cycle GHG emission reduction is required.

The default values established for different SAF pathways under CORSIA are listed in various sections of this report. Fuel producers can apply for certification of their production pathway based on CORSIA regulations. Otherwise, the default values will apply(International Civil Aviation Organisation (ICAO), 2019a) . The baseline life cycle emissions value for jet fuel under CORSIA is equal to 89 g CO2e /MJ.

[33] https://rsb.org/
[34] https://www.iscc-system.org/
[35] https://www.sfiprogram.org/
[36] https://fsc.org/en
[37] https://sbp-cert.org/

Other sustainability criteria are summarised below in Table 13.

Table 13 Sustainability criteria established under ICAO's CORSIA

Theme	Principle	Criteria
1. Greenhouse Gases (GHG)	Principle: CORSIA SAF should generate lower carbon emissions on a life cycle basis.	Criterion 1.1: CORSIA SAF will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Carbon stock	Principle: CORSIA SAF should not be made from biomass obtained from land with high carbon stock.	Criterion 2.1: CORSIA SAF will not be made from biomass obtained from land converted after 1 January 2008 that was primary forests, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
		Criterion 2.2: In the event of land use conversion after 1 January 2008, as defined based on the Intergovernmental Panel on Climate Change (IPCC) land categories, direct land use change (DLUC) emissions will be calculated. If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value will replace the default ILUC value.
3. Water	Principle: Production of CORSIA SAF should maintain or enhance water quality and availability.	Criterion 3.1: Operational practices will be implemented to maintain or enhance water quality.
		Criterion 3.2: Operational practices will be implemented to use water efficiently and to avoid the depletion of surface or groundwater resources beyond replenishment capacities.
4. Soil	Principle: Production of CORSIA SAFs should maintain or enhance soil health.	Criterion 4.1: Agricultural and forestry best management practices for feedstock production or residue collection will be implemented to maintain or enhance soil health, such as physical, chemical and biological conditions.
5. Air	Principle: Production of CORSIA SAF should minimize negative effects on air quality.	Criterion 5.1: Air pollution emissions will be limited.

6. Conservation	Principle: Production of CORSIA SAF should maintain biodiversity, conservation value and ecosystem services.	Criterion 6.1: CORSIA SAF will not be made from biomass obtained from areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area, unless evidence is provided that shows the activity does not interfere with the protection purposes.
		Criterion 6.2: Low invasive-risk feedstock will be selected for cultivation and appropriate controls will be adopted with the intention of preventing the uncontrolled spread of cultivated alien species and modified microorganisms.
		Criterion 6.3: Operational practices will be implemented to avoid adverse effects on areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area.
7. Waste and Chemicals	Principle: Production of CORSIA SAF should promote responsible management of waste and use of chemicals.	Criterion 7.1: Operational practices will be implemented to ensure that waste arising from production processes as well as chemicals used are stored, handled and disposed of responsibly.
		Criterion 7.2: Responsible and science-based operational practices will be implemented to limit or reduce pesticide use.
8. Human and labour rights	Principle: Production of CORSIA SAF should respect human and labour rights.	Criterion 8.1: CORSIA SAF production will respect human and labour rights.
9. Land use rights and land use	Principle: Production of CORSIA SAF should respect land rights and land use rights including indigenous and/or customary rights.	Criterion 9.1: CORSIA SAF production will respect existing land rights and land use rights including indigenous peoples' rights, both formal and informal.
10. Water use rights	Principle: Production of CORSIA SAF should respect prior formal or customary water use rights.	Criterion 10.1: CORSIA SAF production will respect the existing water use rights of local and indigenous communities.
11. Local and social development	Principle: Production of CORSIA SAF should contribute to social and economic development in regions of poverty.	Criterion 11.1: CORSIA SAF production will strive to, in regions of poverty, improve the socioeconomic conditions of the communities affected by the operation.
12. Food security	Principle: Production of CORSIA SAF should promote food security in food insecure regions.	Criterion 12.1: CORSIA SAF production will, in food insecure regions, strive to enhance the local food security of directly affected stakeholders.

8. The essential role of policies in SAF development and commercialisation

There is a consensus that the "right" policies will be essential if the aviation sector is to meet its climate targets. However, several challenges currently limit the development of SAF. They include:

a) The cost differential with conventional kerosene (jet fuel) and the current higher costs of producing SAF

b) Limited availability of cost-effective/sustainable SAF feedstocks

c) Limited investment and the high cost of financing SAF fuel production infrastructure

d) Competition for resources and incentives with other sectors (e.g., road transport, renewable power) (ICAO CAEP, 2022).

As the cost of SAF production is substantially higher than conventional petroleum jet fuel, commercial development and deployment of SAF cannot occur without policy intervention (ICAO CAEP, 2022). Thus, the development of SAF since the last Task 39 report published in 2021 can largely be ascribed to the strong policy measures that have been introduced in the US and EU.

8.1 Policies that promote SAF in the USA

The USA has several policies that promote biofuels at the federal and state levels, including the long-standing Renewable Fuel Standard (RFS2) and various blenders tax credits for diesel and gasoline. States can also create additional policies and incentives that are stackable with federal policies. The most prominent state policy is California's Low Carbon Fuel Standard (LCFS), which has been emulated in other jurisdictions such as British Columbia, Oregon, and Washington.

Until recently, aviation and jet fuel were not regulated under this legislation. However, the RFS2 and the California LCFS now include aviation in their policies. In 2022, the Inflation Reduction Act (IRA) was adopted, and it includes significant incentives for SAF through a blender and producer tax credit. This policy is seen as a "game changer" for SAF development and commercialization.

8.1.1 The US's Inflation Reduction Act (IRA)

The Inflation Reduction Act (IRA) was passed in August 2022 and includes widespread policy measures to support renewables and biofuel production. It also includes a new SAF Blenders Tax Credit (BTC) to support the sale and use of SAF. The BTC provides an economic incentive that helps bridge the price gap

between conventional/fossil-derived jet fuel and SAF. To qualify, SAF must be blended in the US and uploaded to an aircraft in the US. The BTC results in $1.25 per gallon over a period of two years (2023-2024). Eligible SAF must obtain a minimum of a 50% CI reduction (compared with conventional jet fuel), with an additional one cent per gallon (capped at $1.75) for each additional % reduction in CI. In response, several US SAF producers have announced efforts to reduce the carbon intensity of their fuels by additional investment in renewable electricity, green hydrogen, and carbon capture and storage (CCS). Consequently, linking incentives with increased carbon intensity reduction should support the higher investment costs resulting from the need for additional infrastructure.

Although fuels approved under ASTM D7566 qualify, under ASTM D1655, only the co-processing of FT liquids from biomass can qualify for the BTC. A SAF co-processed qualified mixture must be produced in the United States and any co-processed liquid fuel that is imported into the United States is ineligible for the SAF credit. Only that portion of the SAF that is co-processed and can be attributed to the SAF FT hydrocarbons (derived from biomass) is applicable for the SAF credit.

Under the IRA, emissions carbon intensity (CI) reductions must be measured using the ICAO CORSIA LCA method. “Or any similar methodology that satisfies the criteria under § 211(o)(1)(H) of the Clean Air Act (42 U.S.C. 7545(o)(1)(H)), as in effect on August 16, 2022”. However, on December 15, 2023, the U.S. Department of the Treasury and the Internal Revenue Service (IRS) released a guidance document [38] which approves the use of the US GREET model under these provisions. An updated model will be completed by March 1, 2024. It will include GHG reduction practices within the life cycle analysis, including carbon capture and storage, renewable natural gas, renewable electricity and climate-smart agricultural practices. These practices are not currently included under the CORSIA life cycle methodology [39]. The inclusion of these practices could substantially lower the carbon intensity of SAF and allow SAF producers to meet the CI reduction criteria, even in cases where crop-based feedstocks such as corn ethanol is used.

After December 31, 2024, the sustainable aviation fuel, biodiesel, renewable fuels and alternative fuels credits will transition to the clean fuel production credit. The clean fuel production act will only apply to any transportation fuels produced by a taxpayer within the US at qualified facilities. The producer tax credit is 20 cents per gallon if emission reduction limits are not met and $1/gallon where emissions

[38] https://content.govdelivery.com/accounts/USEERE/bulletins/3803404
[39] https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf

reductions are above a certain limit. For the case of SAF, the production credit will amount to 35 cents per gallon if CI reduction limits are not met or $1.75 per gallon where CI reduction minimum is achieved. However, this credit is supposed to terminate on December 31, 2027.

The IRA will extend the biodiesel, renewable diesel, alternative fuels, alternative fuels mixtures and second-generation fuels tax credits until December 31, 2024. The blender tax credit for biodiesel and renewable diesel is $1/gallon and has been routinely extended since its first introduction in 2005, typically for periods of one and two years. However, as the tax credit has also lapsed at times, this has impacted investment in the industry.

The IRA has also established a competitive grant program in support of alternative aviation and fuels, although grants will only be available for projects located in the U.S. that produce, transport, blend or store SAF. It will also support additional infrastructure needed in the downstream supply of SAF to airports. Nearly $250 million (US) in funding will be available to support SAF projects under the program. The IRA also has $500 million (US) to support the development of biofuel infrastructure (e.g., infrastructure improvements for blending, storing, supplying or distributing biofuels) and includes an estimated $18 billion in support of climate-smart agriculture. This aspect should also benefit biofuel producers through the production of lower-carbon-intensive feedstocks.

According to the IRS guidance on SAF credits (Notice 2023-06), a claimant who qualifies for the SAF credit may either claim an excise tax credit or a refundable income tax credit or claim a non-refundable general business income tax credit.

8.1.2 The US's SAF Grand Challenge

The Sustainable Aviation Fuel Grand Challenge was launched by the US as a government-wide commitment and comprehensive strategy to produce 35 billion gallons of SAF by 2050 (enough to meet all jet fuel demand in the US), with an interim target of 3 billion gallons by 2030. The challenge is a collaborative effort of the U.S. Department of Energy (DOE), the U.S. Department of Transportation (DOT), the U.S. Department of Agriculture (USDA) and various other federal government agencies. The strategy's goals include scaling up new technologies to produce SAF at a commercial scale and expanding the production and use of SAF. A major focus is reducing the cost of SAF and enhancing its sustainability.

The SAF Grand Challenge roadmap was developed to outline an integrated government approach, describing coordinated policies and specific activities that should be undertaken by the federal agencies to support achieving both the 2030 and 2050 goals. It is hoped that the roadmap will ensure alignment

of government and industry actions and coordinate government policies so that the goals of the SAF Grand Challenge can be met. This includes coordination of research, development, demonstration and deployment (RDD&D). In addition, modelling and analysis will be shared, including tools, assumptions and insights across the various agencies' research centres. This includes the Department of Energy (DOE) National Laboratories, the Federal Aviation Administration's (FAA) Center of Excellence for Alternative Jet Fuels and Environment (ASCENT) and the US Department of Agriculture's (USDA) Agricultural Research Service, Forest Service, and National Institute of Food and Agriculture.

The roadmap describes six action areas that span all activities that might impact the SAF Grand Challenge objectives of expanding SAF supply and end use, reducing the cost of SAF while enhancing the sustainability of SAF.

The action areas include:

- Feedstock Innovation
- Conversion Technology Innovation
- Building Supply Chains
- Policy and Valuation Analysis
- Enabling End Use
- Communicating Progress and Building Support.

8.1.3 The California Low Carbon Fuel Standard (LCFS) and SAF

The California Low Carbon Fuel Standard (LCFS) was first implemented in 2011 with a goal of decarbonising California by 20% in 2030 and net zero by 2045. The LCFS has played a significant role in biofuel development, helping decarbonize fuels while also impacting air pollution and increasing the fuel efficiency of vehicles. The LCFS sets annual carbon intensity (CI) standards, or benchmarks, which are reduced over time, encouraging low-CI fuels to replace fossil fuels. It should be stressed that the LCFS lets the market determine which mix of fuels will be used to reach the program targets. The fuel suppliers/producers must carry out an LCA, and the associated pathways must be approved (specific CI for each producer & feedstock pathway) by the State. The incentives, derived through the credit value of fuels, are stackable with any incentives that are also obtained via the federal U.S. Renewable Fuel Standard (RFS2) and under the IRA.

Although the California LCFS provides for a credit clearance market where credits can be purchased to achieve compliance, there is a maximum price ceiling on credits. This amounted to USD $239.18 in 2021 but is adjusted annually for inflation. In 2018, the California Air Resources Board (CARB) included

alternative aviation fuels as an "opt-in", allowing these fuels to earn compliance credits in the fuel pool without incurring any debits. Credits can be earned on the basis of the carbon intensity of the fuels relative to a declining baseline for fossil jet fuel. Although this policy goes some way towards bridging the price gap between SAF and conventional/fossil-derived jet fuel, it does not obligate its use. One challenge is that renewable diesel is able to earn higher credits, making SAF uncompetitive and favours the production of renewable diesel rather than SAF.

8.1.4 U.S. Renewable Fuel Standard and the role of RINs

The Renewable Fuel Standard (RFS2) requires any transportation fuel sold in the U.S. to contain a minimum volume of renewable fuels, (termed Renewable Volume Obligations (RVOs)) with the RVOs imposed on fuel refiners, blenders and importers. Renewable Identification Numbers (RINs) are used to track the compliance of obligated parties and serve as proof that they met their RVO. RINs are the system's credits and act as an incentive for fuel producers.

The RFS was recently amended to include renewable jet fuel as an "opt-in" option, to earn RIN credits without establishing an RVO for aviation. SAF can be eligible for either D4 biodiesel, D5 advanced biofuel or D7 cellulosic diesel RINs. Minimum emission reduction criteria apply to different RINs, e.g., D4 (50% reduction in CI), D5 (50% reduction in CI) and D7 (60% reduction in CI). In 2022, D4 RINs peaked on April 28 at $1.91 per gallon. Under the RFS, SAF can generate 1.6 RINs per gallon, while renewable diesel earns 1.7 RINs. Consequently, this puts SAF at a disadvantage when compared to renewable diesel. According to Platts, renewable diesel has a USD$0.1655/RIN premium over SAF in Q3/2021. This acts as a potential disincentive for companies to make SAF rather than allocating 100% of their production to renewable diesel.

However, the stackable nature of various incentives may alleviate this disadvantage as biodiesel and renewable diesel can currently earn a USD$1 per gallon blenders tax credit. However, under the new Inflation Reduction Act, SAF will be able to earn between USD$1.25-$1.75 per gallon. This may act as a sufficient incentive for renewable diesel producers to divert some of their production to SAF.

8.1.5 LCFS in Oregon and Washington State

Under the Oregon Clean Fuels Program, SAF producers can register as voluntary parties and earn credits on an "opt-in" basis. Various pathways to alternative jet fuel production via hydrotreatment have been approved. The default carbon intensity values have also been publicised, and they are identical to the

ones developed by the California Air Resources Board (CARB). While feedstocks derived from plant oils are accepted, palm oil and palm derivatives are excluded.

A similar approach is being followed by the Washington State Clean Fuels Standard.

8.1.6 Sustainable Aviation Fuel Credit in Illinois

A Sustainable Aviation Fuel Credit was introduced in the Illinois Senate on 9 January 2023, and this will provide a SAF purchase credit for a period of 10 years, from June 1, 2023, to January 1, 2033. Any SAF sold to or used by an airline in Illinois will earn a credit of USD$1.50 per gallon of SAF purchased (Invest in Illinois Act, 2023)(Invest in Illinois Act, 2023)(Invest in Illinois Act, 2023)(Invest in Illinois Act, 2023)(Invest in Illinois Act, 2023). However, the eligibility of SAF is limited to ASTM D7566 certified SAF or co-processing of FT liquids under D1655. Although from now until June 1, 2028, SAF can be derived from biomass resources, waste streams, renewable energy sources, or gaseous carbon oxides, beginning June 1, 2028, the SAF must be derived from domestic sources of biomass. SAF made from any palm derivatives is not eligible. The SAF must achieve at least a 50% lifecycle GHG emission reduction based on the ICAO CORSIA method or the Argonne GREET model (inclusive of agricultural practices and CCS).

This credit can also be stacked with federal credits.

8.1.7 Sustainable Aviation Fuel Credit in Minnesota

Minnesota also enacted a Sustainable Aviation Fuel Tax Credit on March 23, 2023. The S.F. 2723 establishes a refundable sustainable aviation fuel ("SAF") tax credit and related sales tax exemption for blenders and producers of sustainable aviation fuel. The Act provides a refundable income and corporate franchise tax credit equal to $1.50 per gallon of SAF produced or blended in Minnesota, which will be in force until January 1, 2035. The commissioners of revenue and agriculture must prescribe the manner in which the credit will be claimed. The Act specifies that SAF is exempt from aviation gasoline and jet fuel taxes and exempt from sales tax. Section 6 of the Act also provides a sales tax exemption for construction materials and supplies used or consumed in, and equipment incorporated into, the construction, reconstruction, or improvement of a facility that produces or blends SAF.

8.1.8 SAF credit in Washington State

A SAF tax incentive to manufacture and purchase SAF was also implemented in Washington State. The aim is to incentivize fuel producers to build SAF production facilities in Washington by creating a business and operations tax rate of 0.275% for the manufacture and sale of sustainable aviation fuels. The tax

incentive will go into effect July 1, 2024, but only after a facility capable of producing at least 20 million gallons of alternative jet fuel is operating in Washington. It will be applicable for 10 years.

The credits are equivalent to one dollar for every gallon of alternative jet fuel, and the amount will increase depending on the reduction in emissions. For example, an alternative fuel that is 50% cleaner than conventional fuel would generate a $1 credit. Fuel that is 51% cleaner would receive a $1.02 credit, increasing by each percent up to $2 per gallon.

8.2 Policies that promote SAF in Europe- Fit for 55 and the ReFuelEU mandate

The EU, as part of their Fit-for-55 strategy, proposed developing a mandate to encourage blending SAF into jet fuel, including aggressive targets to 2050. This included a sub-mandate for SAF based on power-to-liquids. In addition to the EU, other European countries, including Norway, Sweden and the UK, have established separate policies for SAF.

In July 2021, the European Commission developed climate, energy, land use, transport and taxation policies aimed at reducing the EU's net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels (the "fit for 55" package) (Think Tank, 2022)(Think Tank, 2022)(Think Tank, 2022)(Think Tank, 2022)(Think Tank, 2022). The package included a proposal to ensure a level playing field for sustainable air transport. Thus is also known as the ReFuelEU Aviation initiative.

The new regulation contains the following main provisions:

(a) The obligation for aviation fuel suppliers to ensure that all fuel made available to aircraft operators at EU airports contains a minimum share of SAF from 2025 and, from 2030, a minimum share of synthetic fuels, with both shares increasing progressively until 2050. Fuel suppliers will have to incorporate 2% SAF in 2025, 6% in 2030 and 70% in 2050. From 2030, 1,2% of fuels must also be synthetic fuels, rising to 35% in 2050.
(b) The obligation for aircraft operators to ensure that the yearly quantity of aviation fuel uplifted at a given EU airport is at least 90% of the yearly aviation fuel required to avoid tankering practices, which would bring additional emissions from extra weight.
(c) The scope of eligible sustainable aviation fuels and synthetic aviation fuels includes certified biofuels, renewable fuels of non-biological origin (including renewable hydrogen) and recycled carbon aviation fuels complying with the Renewable Energy Directive (RED) sustainability and emissions saving criteria, up to a maximum of 70% with the exception of biofuels from food and feed crops, as

well as low-carbon aviation fuels (including low-carbon hydrogen), which can be used to reach the minimum shares in the respective part of the regulation.

(d) Rules on the competent authorities, to be designated by the member states to enforce this regulation, and rules on fines.

(e) The creation of a Union labelling scheme about environmental performance for aircraft operators using SAF will help consumers make informed choices and promote greener flights.

(f) Data collection and reporting obligations for fuel suppliers and aircraft operators to enable monitoring of the effects of this regulation on the competitiveness of EU operators and platforms.

The ReFuelEU initiative comes into effect on 1 January 2024.

The ReFuelEU mandate does not provide incentives, so it does not reduce the price gap between SAF and conventional jet fuel. However, it does create a "level playing field", as all airlines will be supplied with SAF blends (at a higher price). In contrast, without a blending mandate, airlines that wish to purchase SAF may be placed at a competitive disadvantage as their fuel costs will be higher than those of other airlines that don't purchase SAF.

The Fit-for-55 package[40] includes the following adopted or agreed proposals: reform of the EU Emissions Trading System (ETS) and the Market Stability Reserve (MSR); a new, self-standing ETS for buildings, road transport and fuels for additional sectors (ETS2); revised Effort Sharing Regulation (ESR); the Carbon Border Adjustment Mechanism (CBAM); the Social Climate Fund (SCF); a revised Land Use, Land-Use Change and Forestry (LULUCF) Regulation; updated CO2 emission standards for cars and vans; the Alternative Fuel Infrastructure Regulation (AFIR); FuelEU Maritime; ReFuelEU Aviation; the Energy Efficiency Directive (EED); Renewable Energy Directive (RED); the Regulation on methane emissions reduction in the energy sector; and the associated revision of the Regulation on Fluorinated Greenhouse Gases.

Today, the Fit-for-55 and associated proposals that are still under negotiation with the co-legislators are: the Energy Performance of Buildings Directive (EPBD), the Hydrogen and decarbonised gas market package; the proposal for a revised Energy Taxation Directive; and the revision of the Regulation on CO2 emission standards for heavy-duty vehicles.

[40] Fit for 55 package (COM (2021) 550 final) https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021DC0550

As regards the aviation sector, the share of RES that contributes to green the sector is included within the revised Directive (EU) 2023/2413[41] (RED III) targets for the overall EU transport sector. Specific targets for SAFs up to 2050 have been set by ReFuelEU Aviation[42], that introduced mandates of advanced biofuels and RFNBO into the commercial jet-fuel blend (34% in 2040 and 70% in 2050; including a sub-mandate for synthetic aviation fuels and H2: 10% in 2040 and 35% in 2050). In the short term, the mandate for fuel suppliers is 2% of SAF by 2025, 6% by 2030 and 1.2% of share must also be RFNBO. Such share will be included within the RED III target of advanced biofuels and biogas for transport set at 5.5% (including at least 1% RFNBOs) by 2030. The sustainability criteria to certify SAF eligibility are the same depicted for road transport as set in the Directive (EU) 2001/201843 and Directive (EU) 2023/2413 (RED II and RED III respectively). Finally, REFuelEU also introduced other obligations and rules for aircraft operators and competent authorities to establish new mechanisms to green EU aviation.

As agreed in 2023, in 2026, the Commission will assess an extension of the carbon pricing for the aviation (and maritime) sector. Tackling obstacles to the implementation of alternative fuels with low or zero emissions, such as renewable fuels of non-biological origin (RFNBO) and advanced biofuels, specifically in the aviation industry, is crucial. Prioritizing these fuels for aviation—a sector with limited decarbonization options compared to others that can more readily switch to direct electrification—will significantly contribute to the European Union's climate goals and the broader international efforts to mitigate climate change. It is crucial that the current GHG emissions accounting be improved and harmonized at international level, per the most recent scientific findings. Furthermore, a framework will be established for airlines to effectively track, report, and verify the non-CO2 emissions and broader climatic effects resulting from aviation activities.

The EU Emissions Trading Scheme provisions relating to aviation were changed as follows:

- Phasing out free allowances for the aviation sector by 2026.
- 20 million free 'SAF allowances' will be set aside to incentivise the uptake of SAF in the EU and 5 million allowances will be transferred to the EU's innovation fund for low-carbon technologies.

[41] https://eur-lex.europa.eu/eli/dir/2023/2413/oj
[42] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) https://data.consilium.europa.eu/doc/document/PE-29-2023-INIT/en/pdf
[43] http://data.europa.eu/eli/dir/2018/2001/oj

- Until the start of 2027, EU carbon pricing will apply to flights within the EU/EEA and departing flights to Switzerland and the United Kingdom, maintaining the current ‘stop the clock' mechanism on the international application of the rules.
- In 2026, the Commission will carry out an assessment of CORSIA to see if it is sufficiently delivering on the goals of the Paris Agreement.
- Subject to the outcome of this assessment, the Commission will make a legislative proposal, which could extend the scope of EU emissions trading to departing flights if CORSIA is not sufficiently aligned with the Paris Agreement.
- The deal also provides for a new support scheme to speed up the use of SAF, which will be financed with EU ETS revenues, which are estimated at €1.6 billion.
- It will also create a new system for airlines to monitor, report and verify non-CO2 emissions and climate effects of aviation, which make up two-thirds of aviation's total climate impact.

8.3 SAF-related policies in other countries

The United Kingdom launched a Jet Zero strategy, which commits UK domestic aviation to achieve net zero emissions by 2040 with a 10% SAF penetration by 2030. The strategy outlines a goal of all UK airports emitting zero emissions by 2040. The SAF mandate will operate as a greenhouse gas emission reduction scheme with tradeable certificates. The SAF must deliver at least a 50% reduction in GHG emissions and meet strict sustainability criteria. Any SAF made via the HEFA route will be capped, and power-to-liquid derived SAF will be supported through a sub-target. A new 165 million-pound Advanced Fuels Fund was established to support technology development. The goal is to have five commercial SAF facilities under construction by 2025.

Japan's Ministry of Economy, Trade and Industry (METI) plans to introduce a sustainable aviation fuel (SAF) mandate to achieve the country's target of 10% SAF use by 2030, as well as tax exemptions and subsidies as investment promotion measures JPY337billion (USD22.4 billion Equivalent) for 5 years FY2024-2028. Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) projects the country's 2030 SAF consumption will be 1.72mn kilolitre/yr (10.8mn bl/yr), comprising 880,000 kl by Japanese airlines, and 840,000 kl by a non-Japanese air carrier. Domestic supply capacity is forecast to be around 1.92mn kl in 2030 by METI.

In February 2024, Singapore announced that "the country aims for a 1% SAF target from 2026 and plans to raise it to 3-5% by 2030, subject to global developments and the wider availability and adoption of SAF"[44].

In British Columbia, new provisions under the BC LCFS will lead to the inclusion of aviation. Jet fuel will be subject to CI reduction requirements from 1 January 2024. This will require suppliers of jet fuels to meet increasingly stringent annual carbon intensity reduction targets. These are:

Compliance Period	**Percent Reduction for fuel in jet fuel category**	**Target carbon intensity for jet fuel category (gCO2e/MJ)**
2024	0%	88.83
2025	0%	88.83
2026	2%	87.05
2027	4%	85.28
2028	6%	83.50
2029	8%	81.72
2030 and subsequent compliance periods	10%	79.95

As these requirements may be met with over-compliance in the gasoline or diesel fuel categories, the Act also introduces a requirement for a minimum renewable content in the jet fuel category. Suppliers of fuel in the jet fuel category will be required to ensure that the volume of jet fuel they supply in a compliance period contains at least 1% renewable fuel content by volume starting in 2028, 2% renewable fuel content by volume in 2029 and 3% renewable fuel content by volume in 2030 and subsequent compliance periods.

From 2028, the renewable fuel content requirements for the jet fuel category must be met with non-fossil-derived alternatives to jet fuel, as prescribed in the Regulation. This may not be met by over-compliance with the renewable fuel content requirements in the gasoline or diesel fuel categories.

9. Conclusions

Significant progress has been made in the development and commercialisation of SAF since the last IEA Bioenergy Task 39 report, with biojet/SAF production rapidly increasing and more than a hundred facilities planned. IATA estimated (SAF) production reached 300-450 million liters in 2022, a significant increase from the 2021 production of 100 million liters. Although IATA estimates 69 BLPY of total

[44] https://www.reuters.com/sustainability/singapore-require-departing-flights-use-sustainable-fuel-2026-2024-02-19/

renewable fuel production by 2028, they did not specify the amount of SAF/biojet fraction that might be available. As covered in this report, this is probably overly optimistic, based on announcements, planned facilities and the multiple challenges that remain to be resolved. Although groups such as Argus report that 142 new SAF facilities are planned, they are at various stages of development.

The lipid/HEFA (hydrotreatment upgrading of fats, oils and greases) pathway to making SAF is currently the only fully commercial pathway and will remain the main supplier of SAF by 2030. However, actual SAF/HEFA production will rely on shifting renewable diesel (from lipids) to SAF and will be driven by policy. “Pioneering” commercial scale facilities for gasification-Fischer Tropsch and Alcohol-to-Jet are either complete or nearing completion, such that the likely cost and CI of the routes to SAF can be better determined. Lower carbon intensity jet (LCIJ) fuel can be obtained via co-processing, and several petroleum refineries in Europe are already producing LCIJ (e.g., BP, Repsol, OMV, ENI, TotalEnergies) and several other refineries are likely to follow. Other technologies, such as Power-to-Liquids (PtL), are at lower TRL levels and mandates such as ReFuelEU, which requires 600 MLPY of e-kerosene by 2030, might prove challenging to fulfill.

As well as the technical challenges outlined in this update, it is probable that SAF-specific policies will have the greatest impact on SAF expansion. Although the lipid-to-biojet process supplies the vast majority of SAF that is used to date, there will be increasing competition for lipid feedstocks from bio/renewable diesel producers. Although technology will play a role in resolving this dilemma, it will likely be the use of enabling policies that will facilitate the aviation sector to attain its 2030 and 2050 decarbonisation targets.

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