BC-SMART Low Carbon Fuels Consortium

Decarbonising Long-Distance Transport

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Biojet/SAF: a summary of the recent IEA Bioenergy Task 39 report on this topic

From the BC-SMART Secretariat

Members of the BC-SMART secretariat are fortunate to be part of the IEA's Technology Cooperative Program (TCP) that looks at decarbonisation of transport through the increased use of biofuels (www.Task39.ieabioenergy.com). Over recent years, there has been an increasing focus on how to decarbonise the "hard to (green) electrify" sectors such as long-distance transport. One of the benefits of active participation in fora a such as Task 39 is that it provides a platform to compare-and-contrast the various approaches taken by the different member countries. Although there might be limited use of "green" hydrogen and electricity by the aviation sector, as it tries to decarbonise, biojet/Sustainable Aviation Fuels (SAF) will be the primary way in which aviation might meet the decarbonisation targets set by organisations such as IEA, ICAO and IATA. In this issue of the BC-SMART newsletter we have summarised the main "take-home" messages of a recent Task 39 report entitled, "*Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies and policies*".

As covered in more detail, (and as described in our last BC-SMART newsletter) the vast majority of biojet/SAF that is made and used today uses the lipid-to-biojet/HEFA pathway. However, although this process soon needs to be supplemented by other routes to SAF, there is currently no consensus on which pathway is likely to predominate. Hopefully, this issue of the BC-SMART newsletter will help you to decide?

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IEA Bioenergy Task 39 recently published a new report on biojet/Sustainable Aviation Fuel (SAF) which was also sponsored by BC SMART. The report, authored by Susan van Dyk and Jack Saddler, can be downloaded from the IEA Bioenergy Task 39 website (link). This issue of the BC SMART newsletter provides a summary of key conclusions of this report, with a focus on technology commercialisation, challenges and opportunities. The report also gives a detailed summary of the main policies in the USA and European Union that are supporting SAF development.

The SAF space is constantly changing and new announcements for facilities and offtake agreements are published on an almost daily basis. This is a far cry from a few years ago with the rapid developments in this area undoubtedly the result of favourable SAF policies in the USA and EU. The figures below show a breakdown of facility announcements based on technology and distribution by region. Although this information is constantly changing, it illustrates ongoing developments in the SAF area. It should be noted that the largest number of new facilities is based on the HEFA pathway (56), the only technology that is fully commercial. Therefore, it presents the lowest risk from an investment perspective. However, multiple facilities have also been announced for technologies such as power-to-liquids (PtL) (27), alcohol-to-jet (AtJ) (21), and gasification with Fischer-Tropsch (FT) (20).

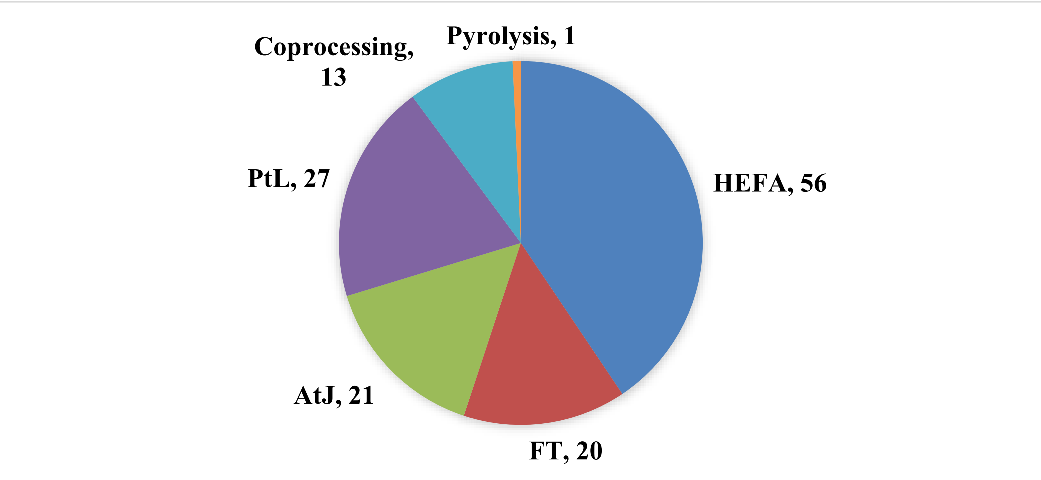


Figure 1. SAF facility - Number of announcements by technology

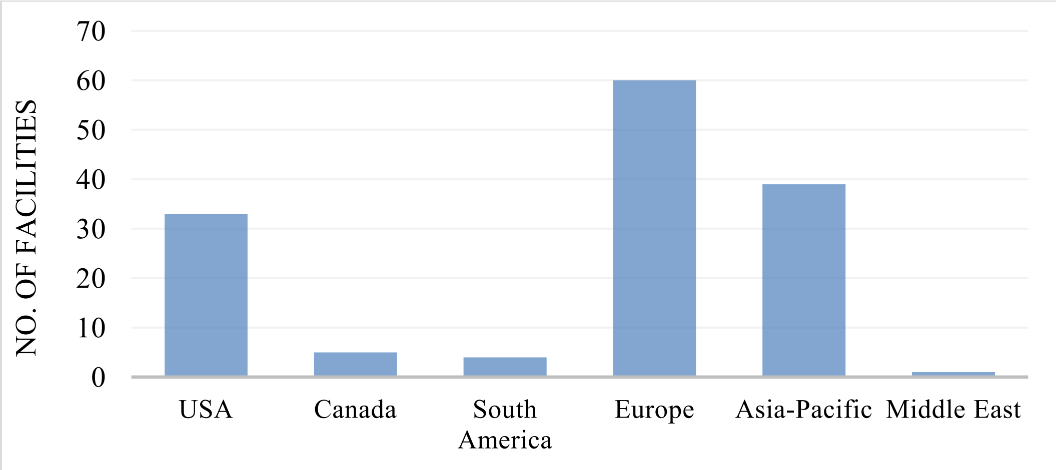


Figure 2. SAF facilities - Distribution by region

One caution is that most of the projects announced have not yet reached Final Investment Decisions (FID). At the recent SAF Congress that took place in Amsterdam in May 2024, biofuel producers highlighted the critical need for off-take agreements in order to obtain financing. According to the ICAO SAF tracker (link), 130 off-take agreements have been announced, amounting to over 53 billion litres of SAF. However, the terms and conditions of off-take agreements are not publicly available. According to biofuel producers, most of the off-take agreements do not offer sufficient security to obtain funding as many off-take agreements undertake the purchase of SAF if the SAF price is competitive with conventional jet fuel. This is unlikely to happen.

The significant difference between SAF and conventional jet fuel is the "green premium" offered to SAF. This results in a major reservation for investors, biofuel producers and airlines that can only be resolved by the right "enabling" policies, as is discussed in more detail below.

In terms of commercialisation of SAF pathways, other than HEFA, there has been some good-and-bad news. The Lanzajet Freedom Pines facility located in Soperton, Georgia officially opened on 24 January 2024 and is expected to start producing SAF by mid-2024. The total capacity of the plant will be about 40 million litres. Lanzajet claims the facility will produce 90% of total product in the form of SAF. As the pioneer AtJ facility, the successful production of SAF will be critical for the further commercialisation of this technology. Based on public information, the source of ethanol used for the process will initially be sugarcane ethanol from Brazil, due to its lower carbon intensity (CI) rating as compared to corn derived ethanol.

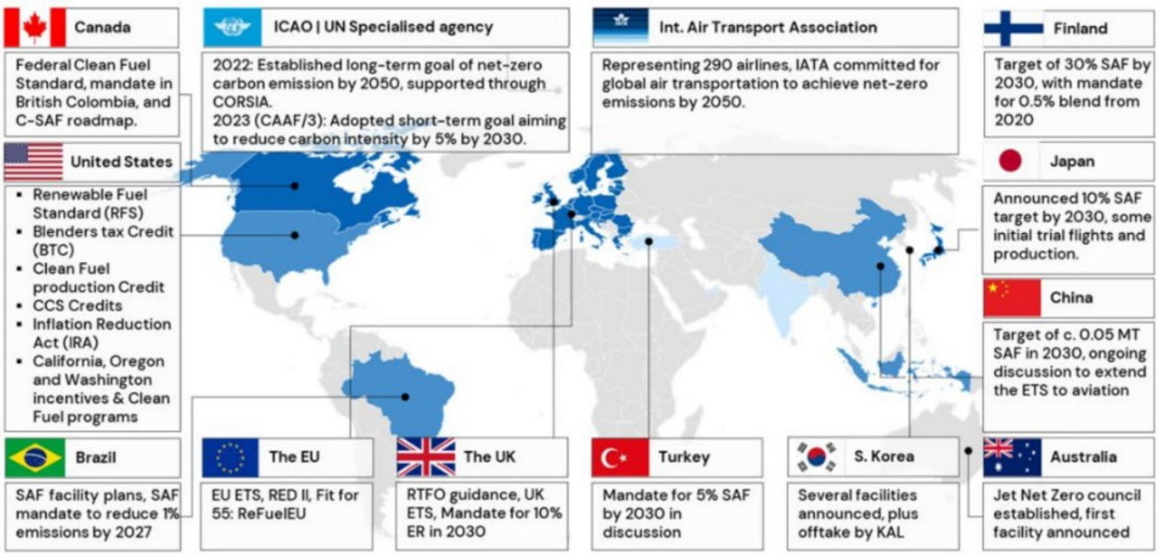
In other (not so good) news, the pioneer gasification facility, Fulcrum Bioenergy, located in Nevada, recently closed its doors (link). The facility was using municipal solid waste gasification with Fischer-Tropsch synthesis. Based on media reports, the company encountered significant problems with issues such as formation of nitric acid which corroded the metallurgy, and a build-up of a cement-like layer in the gasifier, despite a limited volume of FT liquids being produced. The closure of the facility is a blow for SAF production based on the gasification technology. The closure highlights the critical challenge in gasification, such as

the nature of the biomass feedstock and high levels of contamination in feedstocks such as MSW. The summary below highlights the commercialisation status of the various technologies, opportunities-and-challenges and ongoing R&D efforts.

The policy landscape for SAF

Although the predominant policies in the USA and EU can be divided into relative "carrot" (USA) and "stick" (EU) approaches, other countries, such as the UK, have legislated a SAF mandate of 10% by 2030. Although Brazil has developed a SAF policy, this has yet to be finalised, while other countries, such as Japan and Singapore, are in the process of developing policies

Although the ICF "map" below shows existing and proposed global SAF policies, its dynamic nature means that some regions, such as British Columbia, are not yet captured is this summary



Source: ICF Analysis, https://www.itf-oecd.org/sites/default/files/docs/sustainable-aviation-fuels-policy-status-report.pdf, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/policy-net-zero-roadmap.pdf https://www.icao.int/Meetings/a41/Documents/WP/wp_516_en.pdf

Figure 3. Existing and proposed SAF policies around the world

The "carrot" policy approach is exemplified by the US's Inflation Reduction Act (IRA) (and numerous other stackable policies such as the Renewable Fuel Standard, low carbon fuel standards and other state-level policies, e.g., Illinois, Washington State, Minnesota) offer multiple incentives to fuel producers. These policies go a long way to bridging the price gap between SAF and conventional jet fuel. However, the IRA Blender Tax Credit (BTC) only applies for two years and ends at the end of 2024, while the Producer Tax Credit (PTC) is valid for only three years (2025-2027). Consequently, this provides limited security to investors to fund biofuel production facilities. Hopefully, these "enabling" policies will be extended in the future.

The SAF Blenders Tax Credit (BTC) is an incentive of $1.25 per gallon over a period of two years (2023-2024). Eligible biojet/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. After December 31, 2024, the sustainable aviation fuel, biodiesel, renewable fuels and alternative fuels credits will transition to the clean fuel production tax credit (PTC). The PTC will amount to 35 cents per gallon, if CI reduction limits are not met, or $1.75 per gallon where the CI reduction minimum (50% reduction) is achieved.

The "stick" approach is exemplified by the EU's ReFuelEU Aviation mandate which includes an obligation upon fuel suppliers to blend increasingly greater volumes of SAF, up to 2050. The minimum share of SAF supplied at each EU airport should be 2% in 2025 and 6% in 2030, increasing to 20% in 2035, 34% in 2040, 42% in 2045, and 70% in 2050. A sub-obligation for synthetic aviation fuels (e-fuels) is highlighted, increasing from 1.2% in 2030, 2% in 2032, 5% in 2035, up to 35% in 2050. The EU's ReFuelEU Aviation policy also identifies severe penalties for fuel suppliers that do not meet the minimum blending levels. Such penalties will not be less than double the price difference between conventional fuel and the applicable SAF type multiplied by any shortfall quantity. In addition, the volume obligation is also transferred, meaning that the fuel supplier must meet this requirement in the following compliance period.

The recently approved UK policy provides for a SAF mandate that starts in 2025. A minimum blend of 2% of the jet fuel supplied in the UK must be SAF (approximately 230,000 tonnes), 10% SAF target in 2030, and 22% in 2040. This SAF Mandate will operate as a tradeable certificate scheme under which the supply of SAF is rewarded in proportion to its GHG emissions reductions. These certificates can be used to discharge a fuel supplier's obligation under the UK SAF Mandate or be sold to other fuel suppliers. From 2027 onwards, a cap will be set for SAF which is produced via the HEFA pathway, decreasing from 92% in 2027 and gradually lowering to 71% in 2030 and thereafter down to 35% in 2040. From 2028 onwards, 0.2% of the total jet fuel supplied in the UK will have to be SAF produced using the power-to-liquids pathway, with this target gradually increased to 0.5% of the total jet fuel supplied in 2030 and further increased to 3.5% in 2040. The UK's SAF Mandate will include a buy-out option allowing SAF suppliers who do not meet their obligations to pay a price per liter to the government. The price is currently set at £4.70 per liter for the main SAF obligation and £5.00 per liter for the PtL obligation (to be introduced from 2028).

Technology pathways – main conclusions from the Task 39 report

As covered in more detail within the full Task 39 report, there has been significant progress in the commercialization of biojet/SAF technologies as well as considerable investment in related research and development. As there are various challenges associated with the different 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 commercialisation. Although several companies are pursuing the power-to-liquids technology for e-fuels 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.

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, typically, a relatively small fraction (~15%) of the hydrotreated fats and oils fall within the jet range, this percentage can be increased, but at a higher cost and with a loss of overall yield. The development of new isomerization catalysts that can increase the SAF fraction and minimize loss of yield has recently been. However, the decision to shift to increased SAF yields will likely be based on financial considerations, with policy playing a key role, as SAF must compete with renewable diesel production.

The limited availability of waste/lower carbon Intensity (CI) feedstocks (e.g., Fats, Oils and Greases, (FOGs)) will soon restrict the production of bio/renewable diesel and SAF via the HEFA pathway, as crop-derived lipids typically come with a higher cost and CI or may have other sustainability challenges. While alternative oilseed crops (e.g., Carinata, Camelina) could potentially provide additional sustainable feedstock volumes, current commercial availability is very limited.

Trends and challenges of gasification -based technologies for SAF production

Gasification of biomass produces a 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. Although 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.

As Fischer-Tropsch synthesis can achieve direct conversion of biomass to hydrocarbons, which contain a jet fraction, current research and development is mainly focussed on catalysts that have a higher selectivity to the jet fraction, as the straight-run jet fraction from traditional FT synthesis is lower than 40%.

It should also be noted that the gasification process is designed around a specific feedstock, which impacts the feedstock preparation, type of gasification reactor and the syngas cleanup process. While the Fischer-Tropsch process is fully commercial based on coal and natural gas, the technology has yet to be fully commercialized based on biomass or MSW. 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. The recent closure of the Fulcrum Bioenergy facility has demonstrated the challenges for commercialisation of this type of technology. Consequently, until the *first-of-kind* facilities are demonstrated to operate successfully, the ramp-up to full commercialisation will likely be delayed.

As mentioned earlier, although multiple biomass feedstocks can be used by gasification-based technologies, supply chains for these types of feedstocks are not yet 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, it is not clear how the energy-density challenges will be overcome while keeping feedstock costs within a reasonable margin. While there should be no lack of availability of agricultural residues, factors such as a higher ash content, lower density, seasonality, etc., have been shown to present challenges to establishing effective supply chains and biorefineries. For example, supply chain issues based on agricultural residues were shown to play a significant role in the lack of success of cellulosic ethanol. The same challenges are expected for gasification-based pathways using biomass feedstocks.

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

As mentioned earlier, the first small-scale commercial AtJ facility, Lanzajet's Freedom Pines facility in Georgia, is starting to producing biojet/SAF and multiple other facilities based on the AtJ technology are planned across the globe. Several companies are offering integrated AtJ 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 while the methanol-to-jet pathway is in the pipeline for ASTM approval. Gevo has spearheaded the production of isobutanol as the starting alcohol for their isobutanol-to-jet pathway although the company is currently pursuing commercial biojet production based on ethanol. While the majority of announced facilities will be based on ethanol-to-jet, they will differ in their approaches to ethanol production or supply. For example, some companies plan to purchase ethanol, while others plan to integrate ethanol production with the AtJ process. A few companies plan to produce ethanol via Lanzatech's syngas fermentation process, while others are targeting cellulosic ethanol production.

While ethanol from corn, sugarcane or other types of crops are banned for SAF production in the EU, sugarcane ethanol to jet can deliver substantial carbon reductions (57% based on the CORSIA default value). Thus, it can be viewed as a desirable feedstock from an AtJ perspective. Some companies have indicated that this, "paves-the-way" for the eventual development of AtJ technologies based on cellulosic ethanol. However, to date, only a small amount of ethanol has been globally produced from biomass feedstocks. The commercialization of cellulosic ethanol has a long history of challenges (most recently, the

"mothballing" of the Clariant facility in Romania), suggesting that cellulosic ethanol used to make SAF will be limited. For alternative approaches, such biojet produced via gas fermentation or other pathways, a major challenge will be the cost of the ethanol and, therefore, the eventual cost of the SAF.

Although corn ethanol can be used as a feedstock to make biojet/SAF, currently, the carbon intensity reductions are limited. However, the recently approved 40B SAFGREET model, which can be used to calculate the life cycle emissions of corn ethanol, might allow some corn ethanol producers to potentially achieve a 50% reduction in emissions, based on implementation of agricultural practices such as no-till and cover crops. It should be noted that this is currently only applicable to the Blenders Tax Credit portion of the Inflation Reduction Act and will not be applicable under CORSIA. It is also worth noting that reports in the media have suggested that few corn ethanol producers will be able to benefit from these changes to the GREET model.

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

The PtL pathway should be a low-CI route to making SAF as it does not require any biomass feedstocks. However, while it can achieve low carbon intensity SAF, the process will be highly dependent on the source of electricity used for hydrogen production and the source of CO2. The very high cost of production SAF via the PtL pathways will also present a major challenge. While several companies are commercialising PtL technologies, most of them are located in Europe. This is 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. Alternatively, methanol can be produced and converted to 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 the 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 stage of TRL development, 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. Some of the major cost contributors are the CAPEX for electrolysers and the cost of electricity for hydrogen production.

While the electricity/carbon "feedstock" to make SAF via the PtL route is considered by some to be unlimited, in reality, the PtL process is only sustainable if "additional", renewable,

electricity is used. However, the availability of cheap, renewable electricity will be challenging, as renewable electricity will be increasingly required for multiple uses such as heat and power, electric vehicles, etc. Consequently, the production of PtL fuels will be in direct competition with these applications. Also, as the PtL pathway has a *low energy efficiency,* due to energy losses along the conversion pathway, it has been suggested that these other applications 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 via co-processing. Further plans for refinery co-processing (to produce lower CI fuels) have been announced by another seven refineries. Refinery co-processing is based on the insertion of lipids into the hydrotreater (or FCC), with a limit of 5% currently approved by ASTM D1655. However, a subcommittee led by BP is currently hoping to increase the ASTM blend limit to 30%. If approved, this could potentially increase lower carbon-intensive jet fuel production volumes. It should be noted that the current 5% bio-intermediate inserted will not translate into this 5% ending up in the 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.

Conclusions

The SAF landscape is rapidly changing and numerous facilities are planned and under construction, with this partially driven by favourable policies in key jurisdictions such as the USA, EU and UK. As several other countries are also in the process of implementing policies, this will also influence the rate of SAF commercialisation. The full IEA Bioenergy Task 39 report cited in this newsletter describes in more detail the various opportunities-and-challenges for the different biojet/SAF technologies. It also describes the trends in ongoing R&D efforts and the challenges that remain to be resolved to more fully commercialise biojet/SAF production and use. The lipid-to-biojet, HEFA pathway remains the only fully commercial SAF technology and will likely continue to supply the majority of SAF used by 2030. The major challenges for this route are the cost, availability and carbon intensity (CI) of the feedstock and competition with the bio/renewable diesel markets.

Although other technologies are at various stages of commercialisation, in the America's, the ethanol-to-jet process is likely be the next technology to achieve commercialisation. For example, the Lanzajet's Freedom Pines facility has started to produce SAF. Despite gasification/FT's priority in other jurisdictions such as the EU, the closure of the Fulcrum Bioenergy facility in the US will likely result in delayed commercialisation of the gasification pathway. Other pathways, such as power-to-liquids (PtL), are projected to play a significant role in some jurisdictions, with the EU and UK's developing dedicated sub-mandates for PtL routes to SAF. As discussed, co-processing of oils and fats is a fully commercial process and will provide a quick solution to rapid expansion of low-CI jet volumes in the near term. However, although the ReFuelEU Aviation mandate is encouraging European refineries to produce low-CI jet via co-processing, US refineries are mainly producing low-CI diesel.

One of the benefits of international collaboration, facilitated by organisations such as IEA Bioenergy's Task 39, is that allows a compare-and-contrast of the different strategies being followed in different parts of the world. The biojet/SAF area will continue to expand as it is the primary way in which the aviation sector will decarbonise. Canada and BC, because of the vast distances that need to be covered, is more dependant on aviation than most other counties. Hopefully, this newsletter will give you a sense of international efforts in the biojet/SAF area!

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The BC-SMART secretariat (***www.BC-SMART.ca***)